CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Civil Engineering

Department of Sanitary and Ecological Engineering

ASSESSMENT OF STORMWATER MANAGEMENT IN AYACUCHO, PERU

Master's Thesis

Bc. Francisco Sojka

Supervisor in Czech Republic: Doc. Ing. David Stránský, Ph.D.
Supervisor in Peru: Dra. Iris Domínguez Talavera

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ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE
Fakulta stavební
Thákurova 7, 166 29 Praha 6

ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

Příjmení: Sojka Jméno: Francisco Osobní číslo: 423724

Zadávající katedra: Katedra zdravotního a ekologického inženýrství

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II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce: Zhodnocení hospodaření s dešťovými vodami v městě Ayacucho, Peru

Název diplomové práce anglicky: Assessment of stormwater management in Ayacucho, Peru

Pokyny pro vypracování:
Práce bude obsahovat teoretickou a praktickou část. Teoretická část se zaměří na porovnání přístupu k hospodaření se srážkovými vodami v Peru a České republice (legislativa, normy, preferovaná opatření, návrhové postupy, rozšíření ad.). Praktická část bude orientována na kritické zhodnocení aktuální stavu hospodaření se srážkovými vodami ve městě Ayacucho vč. doporučení ke zlepšení. Dále bude ověřena funkčnost hospodaření se srážkovými vodami na konkrétní lokalitě na území města Ayacucho pomocí srážko-odtokového modelu SWMM..

Seznam doporučené literatury:
Krejčí, V. (2002). Odvodňování urbanizovaných území, NOEL 2000
Butler, D., Davies, W. (2009), Urban Drainage, Spon Press
B. Woods Ballard et al. SuDS Manual (2015), CIRIA
Sheyla Rojas Marmolejo (2018). CÁLCULO DE PRECIPITACIONES Y CAUDALES DE DISEÑO DE SISTEMAS DE DRENAJE PLUVIAL URBANO EN ZONAS DE HUANCAVELICA, JUNÍN Y AYACUCHO, Katolická univerzita Lima

Jméno vedoucího diplomové práce: doc. Ing. David Stránský, Ph.D.

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Podpis vedoucího práce Podpis vedoucího katedry

III. PŘEVZETÍ ZADÁNÍ

Beru na vědomí, že jsem povinen vypracovat diplomovou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je nutné uvést v diplomové práci a při citování postupovat v souladu s metodickou příručkou ČVUT „Jak psát vysokoškolské závěrečné práce“ a metodickým pokynem ČVUT „O dodržování etických principů při přípravě vysokoškolských závěrečných prací“.

Datum převzetí zadání Podpis studenta(ky)

I hereby declare that I composed the thesis entirely myself, that it describes my own research and the used ground work is cited in enclosed list.

In Prague ....

Acknowledgements

I would like to thank my supervisor Doc. Ing. David Stránský, Ph.D. for his incredible approach and patience with a procrastinating student. Another thank you deserves my supervisor in Peru, Dra. Iris Domínguez Talavera for her kindness and guidance. And at last my girlfriend, for her support and mischievousness.

Content

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1 Annotation

The objective of this master's thesis is to discuss differences in legislation, climatic conditions and approach towards urban stormwater drainage in the Czech Republic and Peru. It continues with the description of the city of Ayacucho and its stormwater drainage system. Next chapter analyses the data needed to create a simulation in the SWMM software. The practical part of the thesis contains analysis of the drainage system mentioned above and results obtained from the simulation. Another part is the application of the measures designed to improve stormwater drainage system, evaluation and comparison of the original state and the modified state of the stormwater drainage system.

Key words: urban stormwater drainage system, precipitation, SWMM software, Peru

Cílem této diplomové práce je zhodnotit rozdíly v legislativě, v klimatických podmínkách a přístupu k odvodnění dešťových vod v České republice a v Peru. Práce pokračuje popisem města Ayacucho a jeho systémem odvodnění dešťových vod. Další kapitola analyzuje data potřebná k vytvoření simulace v softwaru SWMM. Praktický část této práce obsahuje analýzu systému odvodnění dešťových vod zmíněného výše a výsledky získané ze simulace. Další část se zabývá aplikací prostředků vytvořených k zlepšení odvodnění dešťových vod, evaluaci a porovnání původního stavu a upraveného stavu.

Klíčová slova: hospodaření se srážkovými vodami, srážky, SWMM software, Peru

2 Motivation

From the original idea of comparing SDE (stormwater drainage elements) in Peru – specifically Lima, and the Czech Republic due to the different types of climates and progressivity of countries wasn’t left much after my arrival to the city of Lima. Lima is one of the most humid capitals in the world, but also one of the driest with only around 16 mm of annual precipitation [1]. Therefore, stormwater drainage is unnecessary and thus non-existent – in time of the highest need a janitor is hired to sweep the roof of non-evaporated rainwater. Because of that my focus switched to the city of Ayacucho, which is the capital of the Huamanga region south from Lima, in the central part of Peru. This city was struck with an avalanche of mud and stones caused by a torrential rain in the year 2009, proving the necessity of proper stormwater drainage [2]. Peruvian government reacted to this disaster and developed and implemented a plan to deal with this problem in the future.

3 Objectives

The objectives of this thesis are:

- To research and compare the differences in the legislation and climate of the Czech Republic and Peru
- To describe the form of urban stormwater drainage in the city of Ayacucho
- To find and use local data
- To critically analyse and evaluate this stormwater drainage in the SWMM software
- To improve (if possible and necessary) this stormwater drainage

4 Theory and research

4.1 Stormwater and urbanisation

It's a fact that urbanisation changes the natural hydrology of affected area. It changes the landscape through the change of land use and land cover by altering soil characteristics, removing vegetation, replacing pervious areas with impervious etc [3] [4] [5]. There are observations and studies of the negative effects urbanisation can have on stormwater runoff and flood control in urbanized areas. It is mostly the increase of peak runoff, increased risk of flooding in urbanised areas, decrease in water quality, sedimentation due to erosion of natural water beds, decrease in underground water reserves and the overall quality of stormwater and its recipients [6] [7]. With this in mind the necessity of proper urban stormwater management is becoming more and more important. Another issue connected with urbanisation are urban heat islands, which is a phenomenon where urban areas are significantly warmer than surrounding areas [8].

4.2 Stormwater management

"Stormwater management is the effort to reduce runoff of rainwater or melted snow into streets, lawns and other sites and the improvement of water quality, according to the United States Environmental Protection Agency (EPA)." [9]

The main purpose of stormwater management is to detain and remove pollutants from stormwater, to mimic and protect the natural hydrological cycle.

Low Impact Development (LID) are means of retention, infiltration and evapotranspiration of stormwater. Examples are bio-retention cells, rain gardens, green roofs etc [10].

Amongst the most common measures of stormwater management are replacement impervious surfaces for pervious, addition of green areas into the infrastructure of the city, means of retention and infiltration etc.

Figure 1: Example of LID [11]

4.3 Climatic conditions

4.3.1 The Czech Republic

The Czech Republic is a small country in the centre of Europe between Germany, Poland, Slovakia and Austria. Even though small and without an access to the sea, the natural diversity of the country is still rich. Because of its location, four seasons are represented. Spring, Summer, Autumn and Winter, each of them remarkably different than the other and thus creating a relatively large differences between maximal and minimal temperatures [12] [13]. The Czech Republic is often called the roof of Europe – because of its location, there exists an abundance of stream origins and there are no bigger rivers inflowing to the state plus most of the water that rains or originates in this country outflows [14]. Average yearly precipitation for the Czech Republic is 522 mm for the years 1981 - 2010 [15]. The main natural risks of this country are floods and thanks to global warming droughts are becoming a more imminent threat every year. According to the *Köppen climate classification* Czech Republic contains 4 out of 30 possible climates [16].

4.3.2 Peru

Peru is a developing country of South America, located in its western part between Ecuador, Colombia, Brazil, Bolivia, Chile and the South Pacific ocean [17]. Peru is usually divided into three geographical regions – the coast (costa), the highlands (sierra) and the jungle (selva). Because of its size and location It can be said (with a bit of exaggeration) that the country of Perú is diversity. Peru is home to the second highest peak of South America – Huascarán (6 768 m), to the origin of the biggest river of the world – Amazon river, it shares with Bolivia the biggest lake of South America – Lake Titicaca and currently contains 4% of the planet's fresh water reserves. Main natural problems of this country are earthquakes, tsunamis, floods, landslides, mild volcanic activity, soil erosion and desertification [18] [19] [20]. According to the *Köppen climate classification* Peru contains 15 out of 30 possible climates [21]. Because of the size and variation of Peru it would be pointless to mention average precipitation and temperatures of the whole country, so I wrote down only the variables for the city of Ayacucho. The average annual precipitation is 575 mm, minimal temperature was 3.8°C in June and maximal temperature was 25.7°C in November, according to historical data [22].

4.4 Climate change and precipitation

Thanks to climate change it is anticipated that the intensity of global average precipitation, frequency of heavy rainstorms, evaporation, temperature and runoff will rise in most parts of the world [7] [23]. The increase in evaporation can also lead to droughts in some areas [24]. Although there are observations that confirm this increase, there also are observations of a decrease of this trend, meaning there are areas with less precipitation over the years, but the areas with an increase in rainfall are outnumbering the areas with the decrease in rainfall [25].

4.5 Legislative conditions

4.5.1 The Czech Republic

Structure of the legislation in a hierarchical order [26]*:*

- *The Constitution and constitutional acts*
- *International treaties ratified by the Parliament*
- *Statutes adopted by the Parliament*
- *Derived Legislation: government orders and notifications of ministries, legislative acts and ordinances*
- *Norms – ČSN, EN*

Basically the Act No. 183/2006 Coll. “Building act” states, that building plot is always delimited so as to solve, inter alia, infiltration or drainage of stormwater from built-up areas or paved areas, unless their other use is planned [27]. However the obligation to handle stormwater is stated in the Act No. 254/2001 Coll. “Water act”, § 5.

The obligation to fulfil this law falls on the new developer of the property [27].

Sorted by priority there are three options to handle stormwater [27]:

a) Infiltration
b) Retention and controlled drainage to a surface recipient by a separate canalization – meaning preventing the rainwater to mix with wastewater
c) Retention and controlled drainage to a uniform canalization – meaning rainwater and wastewater mix in the canalization

The technical norms used for designing stormwater drainage systems are:

- ČSN 75 9010 “Stormwater soakaways” - which is used for the design of infiltration systems of stormwaters
- ČSN 75 6110 “Drain and sewer systems outside buildings – Sewer system management“ – which is used for stormwater leaving the external drain piping or drained hard surfaces to the place where these waters are discharged into a wastewater treatment plant or to a water recipient

- ČSN 75 6101 “Sewer systems and house connections“ - which is used for the design and implementation of stormwater inlets serving to drain stormwater from the roads and other outdoor areas into the sewer network

4.5.2 Peru

By the legislative decree N°1356 every urban habitation or building must have some kind of stormwater drainage infrastructure in accordance with plans of development and to ensure the runoff of stormwater and prevention of floods. Local governments, within the framework of their powers, are responsible for compliance of this infrastructure. Local governments are responsible for the function and maintenance of the stormwater drainage inftrastructure in their jurisdiction.

According to the Norm OS.060 every new urban housing localized in an area with frequent precipitation same or exceeding 10 mm in 24 h must have rainwater drainage system. The people responsible for those projects must be civil engineers or collegiate sanitary engineer. [28] [29]

As seen above, Peruvian legislation is in need of modification and better specification of requirements. Another problem connected to the Peruvian legislation is the corruption, when projects are left unfinished because of missing funds, or a lot of buildings are allowed to be constructed even though they are not legally suited to be constructed.

4.6 Comparison of the Czech Republic and Peru

4.6.1 Climatic conditions

Climatic conditions of both countries are very different and so the approach must be in pretty much every way. Peru because of its position, size and variability is more sensitive to climatic change, on the other hand the Czech Republic has bigger differences in temperature locally, when for example in the year 2019 in Brno the lowest measured temperature in January was -12.6°C and highest measured temperature was 37.2°C in July [30].

4.6.2 Legislation

The biggest difference in the legislation is the amount of conditions and requirements in the Czech Republic. They are more detailed and extensive, than in Peru.

4.6.3 Data

The biggest advantage of the Czech Republic is the accessibility, amount and versatility of data. Thanks to the institutes like Czech Hydrometeorological Institute and the institutes of European Union there is a lot of both free and paid data, manuals and norms (like DIN from Germany). Also better formulation of legislation in general, the comprehension of what is required and how can it be achieved is more accessible.

On the other hand Peru is very limited in accessibility to data (often because of the nonexistence of data), and difficult applicability of norms, manuals and data thanks to its size and variability.

4.6.4 Urbanisation

Another part that must be mentioned is the great difference in urbanisation between countries. Because of a bigger density of population - 133.96 inhabitants/km^2 in the Czech Republic [31] and 25.81 inhabitants/km^2 in Peru [32], the difference in urbanisation is sizeable. It is mostly due to its difference in size, as seen in Figure 2.

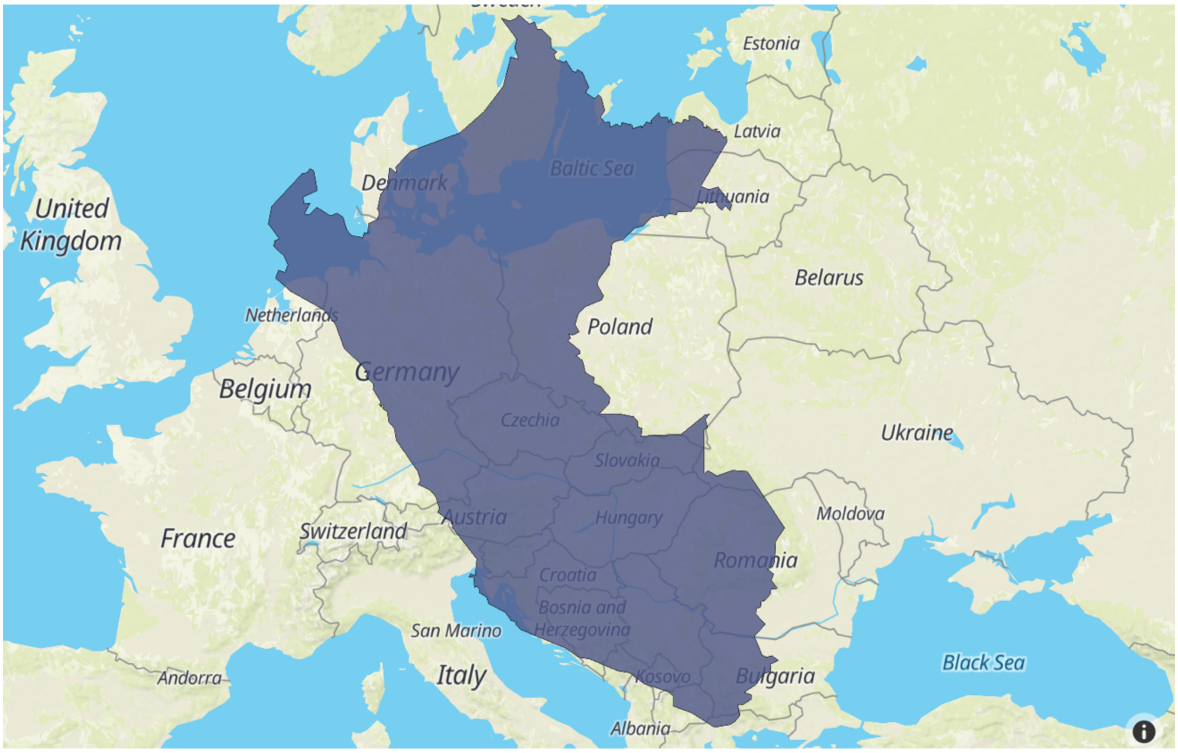

Figure 2: Size comparison of the Czech Republic and Peru [33]

5 Area of Ayacucho

The city of Ayacucho (sometimes still called Huamanga even after its change of name in the year 1825 to Ayacucho) is situated in the Ayacucho region in the central/south part of Peru. It is the capital of this region and also the capital of the Huamanga province. Its population is 180,766 (in the year 2015) and elevation is 2 761 m above the sea level. The climate of Ayacucho is divided in two seasons – the rain season between November and April, and the season of drought for the rest of the year. Average temperature is 15.4 °C and average precipitation is around 575 mm per year, annual average relative humidity around 60%. The Andean mountains are a strong climatic factor in this area [34] [35] [36].

During the rain season the appearance of torrential rains are quite common, leading to floods and sediment accumulation in the most important streets of the city. The streams in its natural channels through which water flows during the rains, that cross the city of Ayacucho are located on the left and on the right bank of the river Alameda to which they contribute to [37].

Among the most important streams are:

San Martin:

- This stream originates in the upper part of the hill Buena Vista, part of the water drains superficially through the ditch of the road Libertadores and the other part drains to the centre of the city. Because of this factor the problem of sedimentation is created in the crossing of the avenue 28. de Julio and street San Martin.

Chaquihuayco:

- This creek originates in the hill Yanama and continues through Asociación de la Victoria de Ayacucho, Cooperativa Ciudad de las Ameritas, Seňor de Arequipa, León Pampa to its outflow to the river Alameda at the height of the Barrio San Sebastián.

Chupas:

- Originating in the Asociación Wari Sur, the creek Chupas crosses the Asociación Los Olivos to its outflow in the creek Chaquihuaco at the height of Avenida Santa Rosa.

Islachayoq:

- This is an important creek beginning in the hill Buena Vista, bordering the Barrio Santa Ana and uniting with the creek Islachayoq at the height of the Barrio Puca Cruz.

Wanchituyoq:

- Originating in the hill Wanchituyoq passes through the Barrio Andamarca to its outflow above the park Alameda in front of Avenida Carmen Alto.

6 Stormwater system in the city of Ayacucho

This chapter is a translation of a project coordinated by Dra. Iris Domínguez Talavera: Proyecto de 'Capacitación en sistemas urbanos de alcantarillado para prevención de desastres', proyecto financiado por el Fondo Concursable 2009 para docentes de la PUCP de la Dirección Académica de Responsabilidad Social (DARS) [38].

The system of collectors and stormwater drainage exists to prevent rainwater and sediments reaching the historic centre of the city, to decrease the damage done to private and public properties during the rain season and to prevent sedimentation in the streets of the city Ayacucho, which otherwise leads to clogging up and thus collapse of the drainage system already built.

Although the floods are common and the need of a proper drainage system seems necessary, it must be said that it is not a priority number one. Even though the environmental situation of the cities of Perú has shown an increase in quality, the high number of social problems, high occurrence of environmental diseases and inequality in the access to basic services pushes the importance of urban environment quality, and so the importance of stormwater urban drainage, to a lower position in the ladder.

This thesis will focus on the northwest part of the city – that is the part most affected by torrential rains and floods and also the part where the deaths and damages took part in the year 2009. Following a study/project created before the year 2009 and updated and set in motion after the year 2009, the drainage situation in the city can be described approximately as seen in the next chapters.

In Figure 3 is a map of climatic risks in the city of Ayacucho. The purpose of this map is to show and better understand why is the northeast part of the city most exposed and endangered by stormwater and sediment flow. The whole map can be seen in attachments.

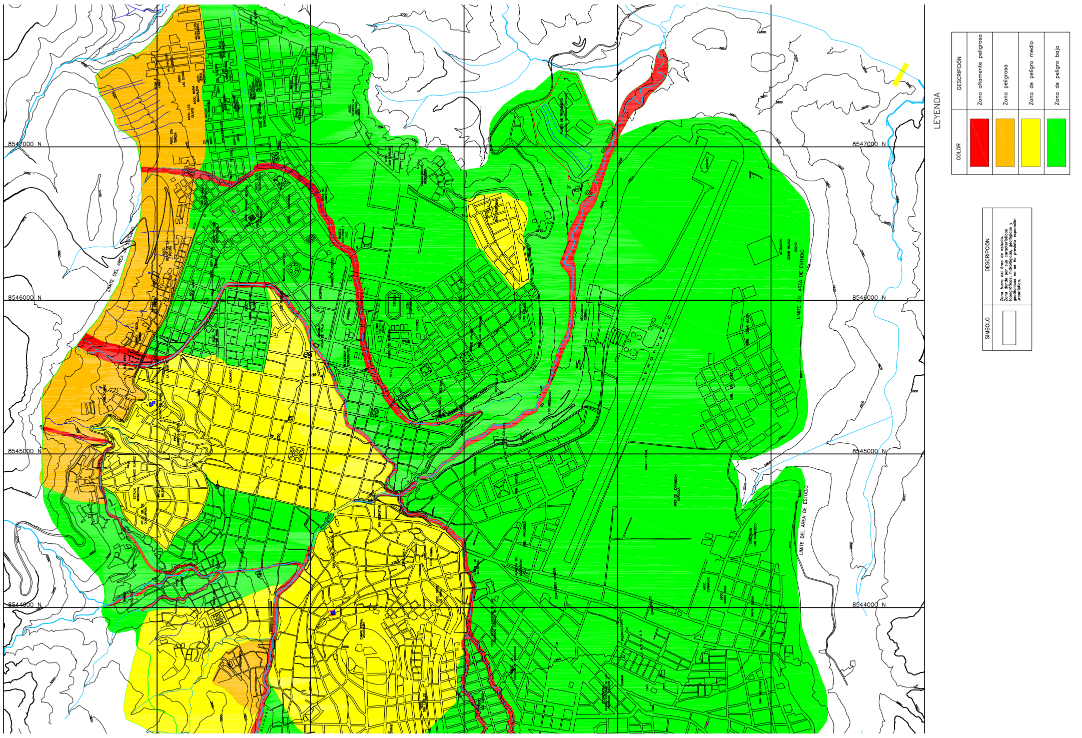

Figure 3: Map of climatic risks in the city of Ayacucho [39]

The majority of the floods has a starting point in the higher and medium parts of the slopes of the hill La Picota. For this reason the project for the reconstruction and improvement of the drainage system has been divided into three zones which interacts with with each other.

Zone 1 is defined between the road Libertadores Wari and the creeks Puca Puca and Accohuayqo.

Zone 2 is in the middle part of the city, between the road Libertadores Wari, street Libertad, Avenue 26 de Enero and the creek Puca Puca which crosses with the creek Arroyo Seco.

Zone 3 is between the street Libertad, Avenue 26. De Enero and the creeks Arroyo Seco and Tarahuaycco which crosses with the creek Alameda.

The city of Ayacucho is crossed from the southeast to the northwest by the river Alameda and on the left bank subsidized by the waters of the basins of the creeks Puca Puca, Prolongacion San Martin, Alto Perú, Yanaccacca, Piscotambo and Accohuayco. Through these natural drains is stormwater evacuated and the flooding of the city partially regulated.

6.1 Zone 1

Zone 1 is situated in the higher parts of the city, between the road Libertadores Wari and the creeks Puca Puca and Accohuayqo. That means most of the sediment flow begins in this zone.

Figure 4: Zone 1

The creeks Yanaccacca and Accohuayco are partially directed through reinforced concrete walls and cyclopean concrete forming open channels that delivers stormwater to the river Alameda and to the next creek Totorilla. However these sewer drains do not satisfy the city's drainage requirements for two fundamental reasons: the first one due to main and missing sewer lines in the Zone 3 and the second because the existing sewer lines do not fulfil their function due to missing catchments and complemental works that would redirect the stormwater to previously mentioned sewer lines, in addition to the necessity of more drains.

The road Libertadores located on the slope of the hill La Picota behaves like a trench thanks to which the inflow of stormwater and sediments entering the city is diminished.

Before the construction of the road Libertadores the influx of the basin of the creek Puca Puca and the Prolongacion San Martin poured in through the street San Martín to the center of the city. This creek was interrupted by the road Libertadores and the stormwater was redirected to the basin of the sewer line Yanaccacca through the basin of this road, however the movement of the sediments and solid parts continues to the urban areas. The stormwater runoff from the basin downstream the road Libertadores continues to ingress the city through the San Martín street, leaving behind sediments.

The starting point of the sewer line Yanaccacca, which is the most important sewer line of the city of Ayacucho, is in the cross of the road Libertadores and the creek Yanaccacca. It is channelled with concrete walls in 50 % of its length, through a canalization of a trapezoidal shape of simple concrete on its lateral sides and with reinforced concrete in its base. Its route leads through the higher area of the urbanization Emadi, Asociacion Nery Garcia Zarate, by the back of the former Guaman Poma de Ayala to its discharge to the creek Alameda, however it does not have sufficient capacity to drain the stormwater and flow of sediments.

In the creek Accohuayco which has its influx point in the crossing of the roads Independencia and Perez de Cuellar is constructed a reinforced concrete channel with concrete lids in a length of 250 m, which is currently poorly draining the area of this creek down towards the sector of Totorilla creek. This sewer line is called Wari Accopampa and is intended to catch the stormwater of the sectors AA.HH los Artesanos and part of the sediment drag of the road Libertadores Wari.

6.2 Zone 2

Zone 2 is situated in the middle part of the city of Ayacucho, between the road Libertadores Wari, street Libertad and transversally from the creek Puca Puca – Arroyo Seco and the creek Tarahuaycco, it is a part of the urban area of the city.

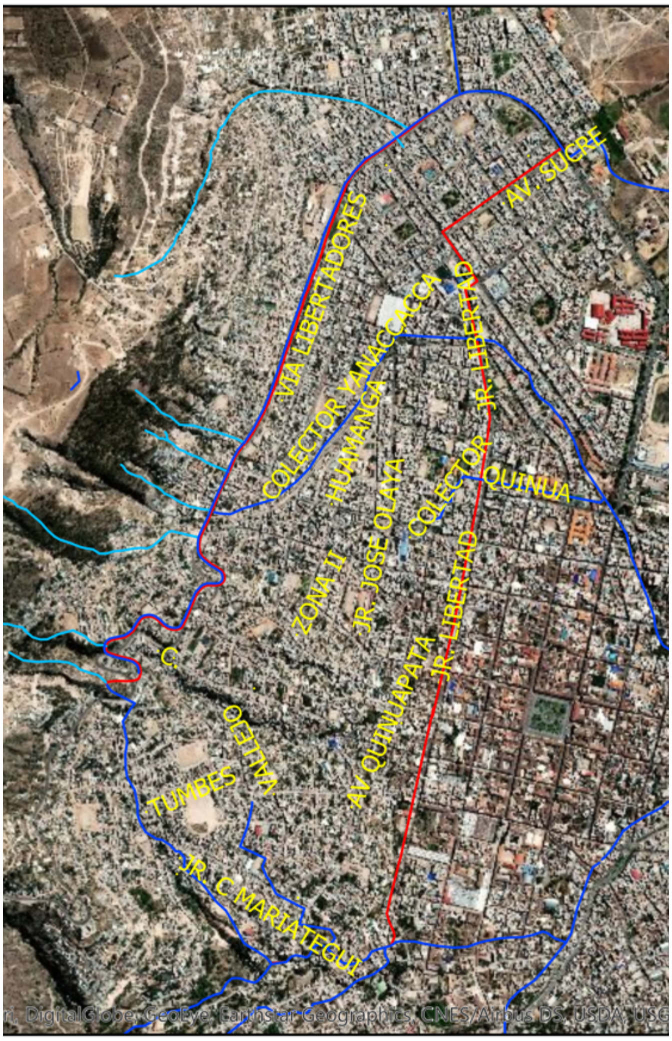

Figure 5: Zone 2

This sector has, in general, its streets from 60 % paved, the remaining streets to be paved are the streets generating sediment flow leading to the historic center of the city.

The creeks Prolongacion San Martin, Alto Perú and Yanaccacca are those which directly contribute to the stormwater and sediment flow in large percentage to the Zone 2 and to the center of the city. Part of this flow is intercepted by the sewer line Yanaccacca.

6.2.1 Yanaccaca sewer line

This sewer line begins at the intersection of the road Libertadores and the creek Yanaccacca, travels through the street Condorcunca all the way to the street Libertad. This section is covered with cyclopean concrete and its section is trapezoidal and receives inflows from two smaller gullies: Huaytarí and Pachacutec, which begins in the middle third of the hill La Picota

The section from the street Libertad to the street Garcilazo de la Vega is a narrow natural channel located between houses.

The part is located between the street Garcilazo de la Vega to the confluence of the streets Asamblea, Quinoa and the road Independencia. It's made of concrete with a rectangular shape, practically 50 % of this section is clogged with sediments, the rest is partially clean all the way to the road Independencia. The cross – section of the channel has been significantly decreased though because of the construction of houses on the banks of the natural channel.

From the street Asamblea or Independencia to the Plazuela Glorieta (street Puno) ends the sewer line Yanaccacca and runs between the houses in its natural channel to its outflow to the river Alameda. In this section the channel behaves like a canalization – there is an infectious hazard because many houses release their wastewaters to this channel.

To this sewer line outflows the stormwaters and sediments from the creeks Alto Perú, Yanaccacca and Prolongacion San Martin. The capacity of the channel is significantly reduced by illegal constructions which closed the natural channel.

It's planned to build a new sewer line with a rectangular shape of a reinforced concrete on the left bank of the road Libetadores Wari to the crossing with the Avenue 26. de Enero with the road Libertadores. The outflow of this sewer line to the sewer line UNSCH.

After the construction of the sewer lines of the road Libertadores Wari and UNSCH, the present problems in the streets down the stream are supposed to diminish by 90 %, for example the stormwater and sediment flow of the sector Pesquero will be neutralized and also the stormwater and sediment flow in the sector Ovalo de Magdalena, etc.

6.2.2 Sewer line Cesar Vallejo

In a similar way it is planned a construction of the sewer line Cesar Vallejo, sewer line located in the northwest part of the city. This construction will allow the caption of the stormwater and sediment flow in its area, with its outflow to the creek Arroyo Seco (creek Puca Puca).

6.2.3 Sewer line UNSCH

There is a sewer line constructed in the north part of the city – the sewer line UNSCH. The beginning of this sewer line is in the crossing of the passage Los Naranjos and the road Universitaria. Its route is through a uncoated channel of an average depth of 4.5 m and 1.2 m wide. Then it’s connected with a reinforced concrete channel of 5 m depth and 1 m wide, which later outflows in the creek Huichccana.

The new sewer line UNSCH will begin in the crossing between Avenue 26. De Enero and the road Libertadores and will continue on the left bank of the road Independencia to the crossing of the passage Los Naranjos and the Avenue Universitaria and will outflow to the creek Huichccana, which is situated in the center part of the road Evitamiento Norte.

6.2.4 Sewer line road Libertadores

This sewer line has its beginning in the left bank of the road Libertadores cca 178 m up of the creek Prolongacion San Martin and the crossing with the road Libertadores. It unites with the sewer line UNSCH in the intersection of the road Libertadores and the 26. De Enero Avenue.

6.2.5 Sewer line Quinoa

This sewer line begins in the intersection of the street Sucre and the street Manco Capac, continues through the street Sucre and the passages of the urbanization EMADI, crosses the street Libertad and continues through the street Quinoa to its outflow in the sewer line Yanaccacca in the crossing of the road Independencia and the street Quinoa.

6.2.6 Sewer line San Martin

This sewer line begins in the intersection of the street Tupac Amaru and the creek San Martin and is supposed to capture the stormwater and sediment flow of the contributing area, this lines continues to the lower parts of the city, passing through the historic center (street San Martin) and outflows in the creek Alameda.

6.3 Zone 3

This zone is situated in the lower parts of the city of Ayacucho between the street Libertad and the creek Alameda, transversely of the creek Arroyo Seco and the creek Tarahuayco. This zone is in the urban part of the historic centre.

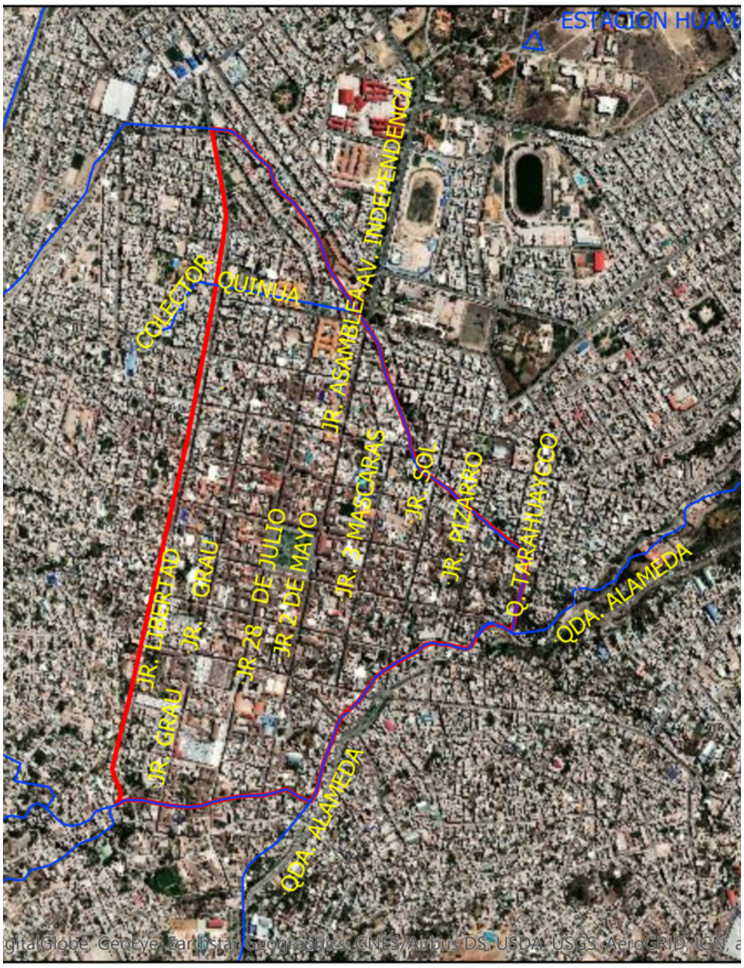

Figure 6: Zone 3

In general the streets of this zone are 100 % paved, but 80% of this streets are damaged or fissured with deep holes in some of the streets.

To stormwater drainage of the historic centre is defective and the principal cause of the presence of stormwater which causes the collapse of the sewer lines in the rain season and increases the road traffic and chaos in the pedestrian parts of the streets.

Since the colonial times the stormwater and sediment flow entering the city was deviated with a small system of drainage in the level of manually excavated creeks.

All the sewer lines located in the historic centre outflow to the creek Yanaccacca and through it to the river Alameda.

The traversal streets in the historic centre collect its waters to the principal sewer lines: 7 Vueltas, Lima – Arequipa, Callao y Cuzco, Bellida, Mariscal Cáceres, Manco Cápac.

Traversal stormwater drainage sewer lines – this lines are: Libertad, Grau y Jiron Garcilazo, 9 de Diciembre, Asamblea y Jiron 2 de Mayo, Tres Mascaras, Sol.

7 Available data analysis

This chapter discusses data needed to successfully build a rainfall-runoff model in the SWMM software. To do that I needed to find precipitation and flow data. Unfortunately there wasn't much to choose from. Institutes like SENAMHI (Servicio Nacional de Meterología e Hidrología) and CORPAC S.A. (La Corporación Peruana de Aeropuertos y Aviación Comercial) can provide precipitation data (in a free or paid form), but those data are not completely suitable for a runoff model. The reason for the unsuitability was the form of the data – maximal precipitation [mm] in 24h. Flow data are completely non-existent. What I found was a master's thesis with the precipitation data transformed into IDF curves, which is not ideal but can be worked with.

Before I discovered that the data from the institute CORPAC are not suitable for the use of this thesis, I was able to enter the restricted area of the Coronel FAP Alfredo Mendívil Duarte Airport in Ayacucho, and take a picture of one of the two rain gauges they are currently using.

Photo 1: Rain gauge at the Coronel FAP Alfredo Mendívil Duarte Airport in Ayacucho. This rain gauge is analogically gathering data, the second rain gauge on the other hand is digitally sending data directly to the headquarters in Lima. Source: Author

The absence of a proper dataset makes a model calibration impossible, which is a great problem that limits the model. Because of this it was decided that I create a model using block rainfall dataset from the IDF curves, after getting the results I alter the model by implementing my recommendations and compare the results thus getting a measurable value.

Table 1: Intensity of rainfall in the area of Huarpo, which Ayacucho is part of [37]

Tiempo de duración		Intensidad de la lluvia (mm /hr) según el Periodo de Retorno						
Hr	**Coef. Duración**	**2 años**	**5 años**	**10 años**	**25 años**	**50 años**	**100 años**	**500 años**
24 hr	1	1.44	1.73	1.93	2.17	2.36	2.54	2.96
18 hr	0.9	1.74	2.10	2.34	2.32	2.86	3.08	3.59
12 hr	0.79	2.30	2.77	3.08	3.48	3.77	4.06	4.73
8 hr	0.64	2.93	3.53	3.93	4.43	4.81	5.18	6.03
6 hr	0.56	3.51	4.23	4.70	5.30	5.75	6.19	7.22
5 hr	0.50	3.93	4.74	5.27	5.95	6.45	6.94	8.09
4 hr	0.44	4.48	5.40	6.01	6.78	7.35	7.92	9.23
3 hr	0.38	5.29	6.37	7.09	8.00	8.67	9.34	10.89
2 hr	0.31	6.72	8.10	9.02	10.17	11.03	11.88	13.84
1 hr	0.25	10.34	12.47	13.87	15.65	16.97	18.28	21.30

8 Critical analysis of designed and realised stormwater drainage elements

The stormwater drainage system as is described in the Chapter 5 is faulty and uncompleted with a lot of space for improvement. The description of faults and recommendations for improvement are below.

The main effects in the city can be divided into the naturally caused and caused by people. Amongst the natural causes are topography, climatic region and the influence of the Andean mountains. The human causes are urbanisation (and the heat island effect caused by urbanisation), deforestation and change of land use.

The city of Ayacucho is suffering greatly because of urbanisation. With the topography of the city variating from cca 2 600 m a.s.l. to 3 000 m a.s.l. any changes to the permeability of the surface and change of land use, i.e. deforestation, are notable. Unfortunately deforestation is still an issue, mostly in the area of the peak Picota, because of the permanent growth of the city, and there are not a lot of permeable surfaces in the city. The areas that are permeable are usually separated by high curbs, mistreated or isolated in general.

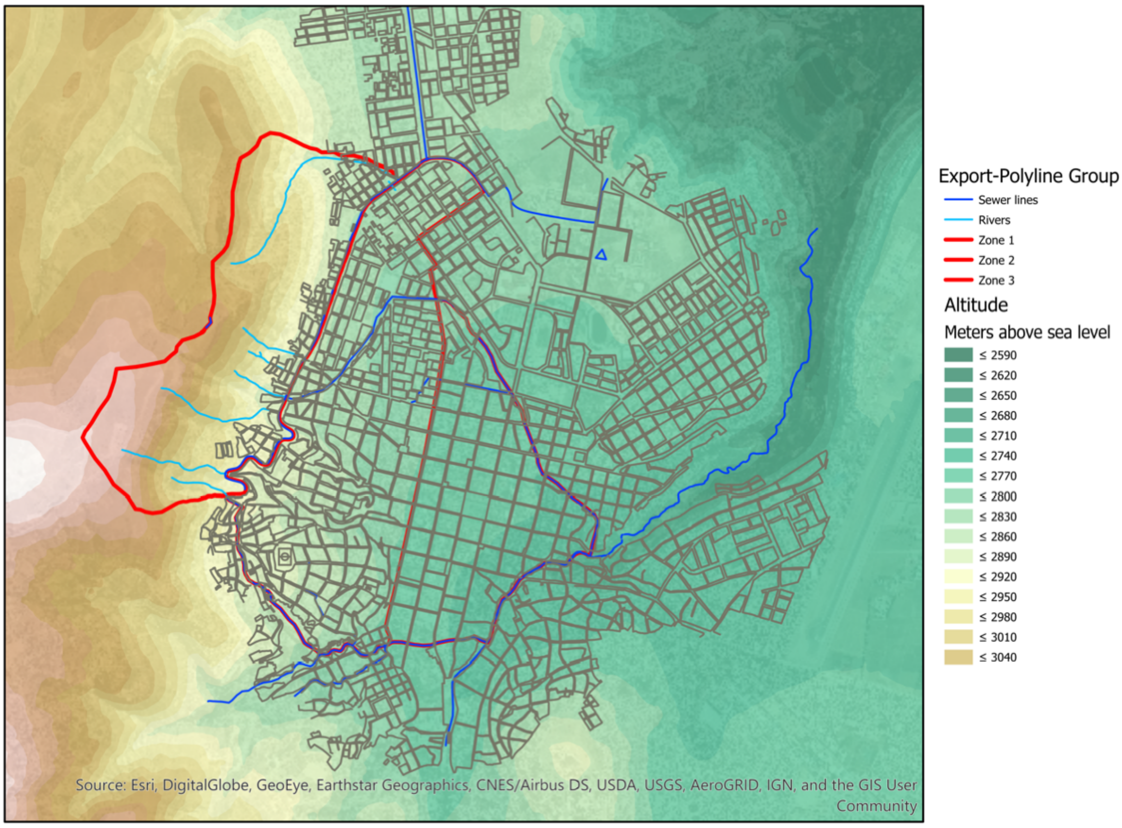

Figure 7: Altitude of the city of Ayacucho. Source: Author

8.1 Measures proposal

Among the general problems in the current stormwater drainage system is for example the trapezoidal cross-section → such a design usually leads to sedimentation in the corner sections. Use of a circular cross-section is more common. Another issue are illegal constructions often blocking natural channels and preventing stormwater flow. Most areas in the city are impermeable, while they could be at least partially permeable. Thrash accumulation is another issue present in the city, often washed by stormwater and clogging the inflow to the current drainage system.

Photo 2: Main square “Plaza de Armas”, in this picture we can see impermeable pavement with a ditch around the grass area. I would recommend changing the pavement from impermeable to permeable and making the area accessible for stormwater by removing the ditch. Source: Author

Photo 3: Close-up of the ditch around the grass area of the Main square – instead of leading the water to flow off this area, I would recommend adjusting the height of the area so the water can flow in the vegetated area. Source: Author

Photo 4: This photo shows the undrained part of the city – most streets of the city look like this. Source: Author

The trend today is sustainable development and stormwater management, meaning slowing the runoff and retention of stormwater. But this approach can be applied after the safety of the citizens is achieved. So it is understandable that the design of the rainwater drainage in the city of Ayacucho is right now designed to evacuate stormwater as fast as possible – this can be changed to respect today's approach. Although because of the old approach, erosion is an apparent problem due to the velocity of runoff.

Photo 5: Erosion and sedimentation in general are an issue as can be seen in this photo – the inflow to the drainage is partially clogged and its capacity is limited. Source: Author

Photo 6: Eroding hillside on the side of the road – source of sedimentation material. Source: Author

Photo 7: Trash is accumulation is also part of the sedimentation problem.
Source: Author

Photo 8: Trash accumulation and sedimentation in the inflow to the to the stormwater drainage system. Source: Author

Photo 9: River Riachuelo (Alameda) which is one of the receivers of stormwater, is eroding its banks during the season of torrential rains, this can lead to stability failure and destruction of nearby constructions. Source: Author

Photo 10: Another receiver of stormwater – due to the high velocity of inflow and erodible banks, the erosion can be very quick and a source of high risk of bank collapse. Source: Author

Photo 11: Another example of high banks erosion due to high velocity of stormwater inflow. Source: Author

Photo 12: In this photo we can see piping leading from the building, draining the roof building and outflowing straight on the street from a considerable height. This is not an unusual sight in the city, in fact most of the buildings are managed this way. Source: Author

Another issue is poorly written legislation concerning the stormwater drainage of habitation, which can lead to some bizarre solutions from the part of the owner.

Photo 13: Illegal sewer outflow leading to the stormwater ditch. Source: Author

Another problem is illegal sewer outflow connected to the stormwater drainage. This leads to infection hazards, is a visual pollution and a source of unpleasant smell.

9 Evaluation of stormwater drainage elements function in a small part of Ayacucho with the SWMM software

“The Storm Water Management Model (SWMM) is a simulation model used for single event or long-term simulation of water runoff quantity and quality in primarily urban areas.” [40]

Construction of the model was made by physical analysis of the city, and with the use of Google Street View. Elevation was measured with a map shown in Figure 7 and made in ArcGIS Pro 10.7. Manning’s n is from the SWMM manual – as shown in Table 2 and Table 3.

Table 2: Manning’s n for open channels [41]

Channel Type	Manning n
Lined Channels	
- Asphalt	0.013 - 0.017
- Brick	0.012 - 0.018
- Concrete	0.011 - 0.020
- Rubble or riprap	0.020 - 0.035
- Vegetal	0.030 - 0.40
Excavated or dredged	
- Earth, straight and uniform	0.020 - 0.030
- Earth, winding, fairly uniform	0.025 - 0.040
- Rock	0.030 - 0.045
- Unmaintained	0.050 - 0.140
Natural channels (minor streams, top width at flood stage < 100 ft)	
- Fairly regular section	0.030 - 0.070
- Irregular section with pools	0.040 - 0.100

Table 3: Manning's n for overland flow [41]

Surface	n
Smooth asphalt	0.011
Smooth concrete	0.012
Ordinary concrete lining	0.013
Good wood	0.014
Brick with cement mortar	0.014
Vitrified clay	0.015
Cast iron	0.015
Corrugated metal pipes	0.024
Cement rubble surface	0.024
Fallow soils (no residue)	0.05
Cultivated soils	
Residue cover < 20%	0.06
Residue cover > 20%	0.17
Range (natural)	0.13
Grass	
Short, prairie	0.15
Dense	0.24
Bermuda grass	0.41
Woods	
Light underbrush	0.40
Dense underbrush	0.80

Because of complexity, manpower and time pressure I chose and simulated only small part of the city – as seen in Figure 8. The area is surrounded with a sewer line UNSCH from the north which makes it an almost enclosed catchment area and is quite orderly with smaller differences in altitude, which makes it easier to simulate.

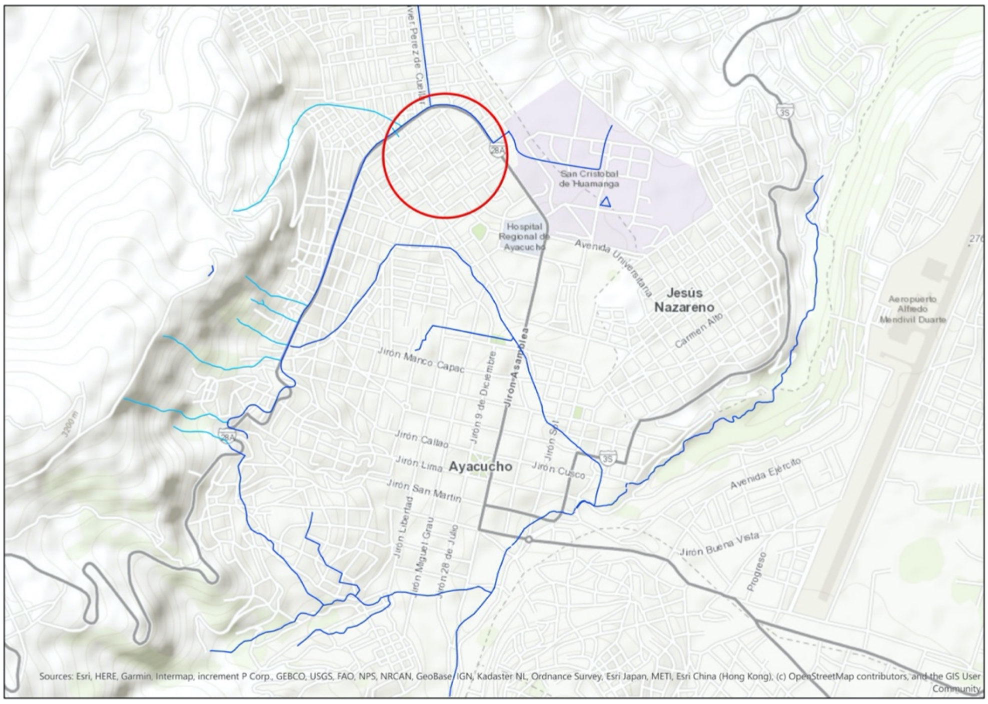

Figure 8: Chosen area in the northern part of the city of Ayacucho that is simulated.

9.1 Information about the constructed model

Table 4: Characteristics for the simulation

Total area [ha]	19.54
Total impervious area [ha]	16.41
Total pervious area [ha]	3.13
Percent of impervious area [%]	84
Number of subcatchments	148
Average area of subcatchments [ha]	0.095
Min altitude [m a.s.l.]	2791
Max altitude [m a.s.l.]	2823
Number of conduits	81
Average roughness (n) of conduits	0.0188

Average length of conduits [m] 65

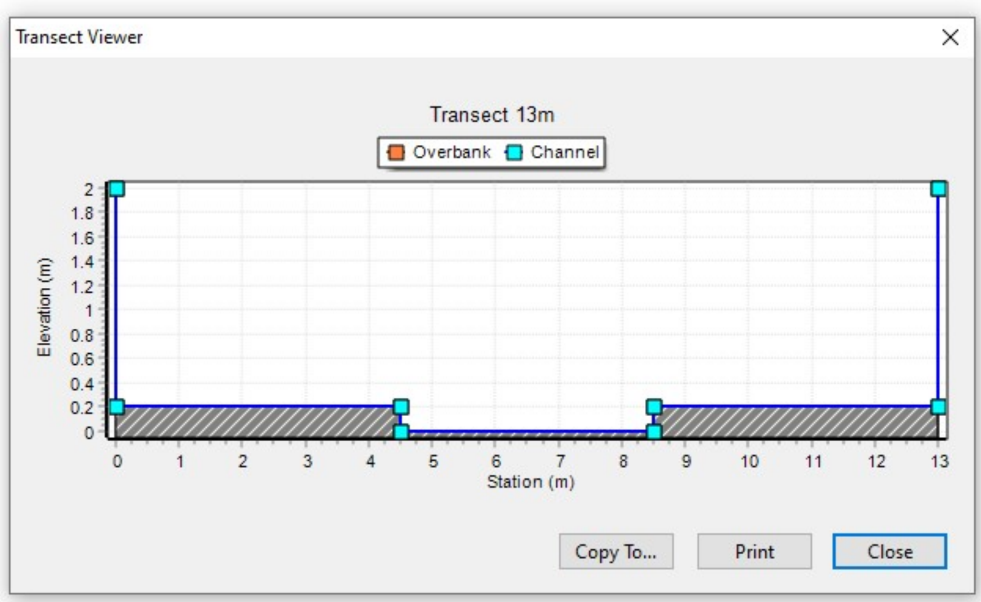

Figure 9: Common profile of the conduit (street), width 13m, road 4m wide. In total 10 conduit profiles have been simulated – varying in the width of the street, width of the sidewalks and existence of drainage channels.

Photo 14: Common appearance of simulated blocks – obtained with Google Maps.

10 Results

This chapter contains simulation results obtained with the SWMM software. Due to the fact, that calibration of the model is not possible, values of the model parameters were chosen according to literature. As a result of this procedure, the model outputs uncertainties have to be considered as significant and the results should be taken with appropriate caution.

I evaluated three variables – depth [m], flow [l/s] and velocity [m/s]. Used data were rains of constant intensity of 5 years of period of return and 50 years of period of return. The IDF storm event data used were for 1h, 4h and 24h each. Precipitation of once per 5 years was used to simulate common rain, precipitation of once per 50 years was used to simulate torrential rain.

When talking about the safety of the citizens, during heavy rains and possible floods there are 2 main risks for the people on the streets – sliding which is mostly dependent on the velocity of the runoff, and tumbling which is mostly dependant on the depth of the water [42]. In Figure 10 we can observe the relationship between these 2 variables. However, results should be again taken with caution – they were obtained during daylight, mostly with trained personnel and in clear water without debris. We can expect none of those conditions during an actual torrential rain [42].

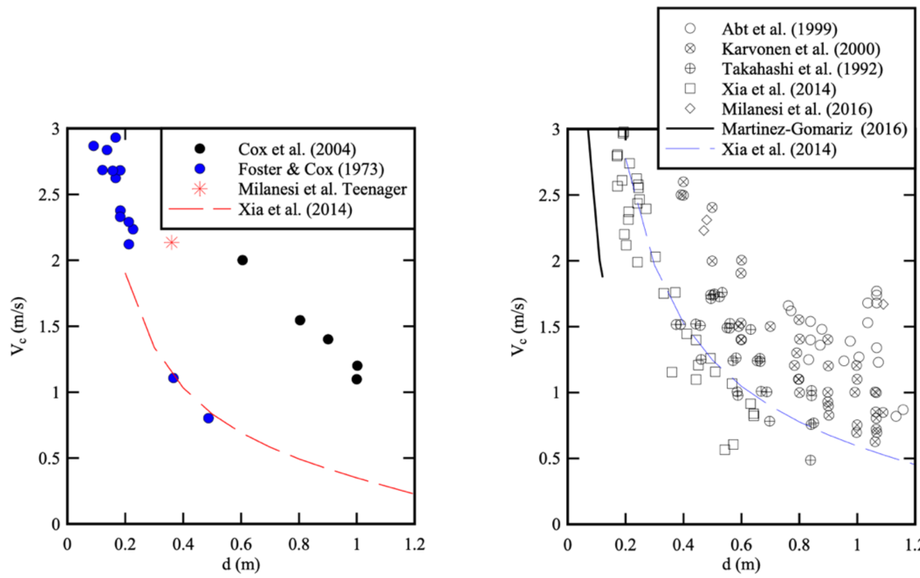

Figure 10: Relationship between characteristic flow velocity and water depth for stability of children (left) and adults (right) [42].

10.1 Current situation in a small part of the city of Ayacucho

These results show the current conditions and stormwater runoff in the northern part of the city. These are the maximal values obtained, location and graphic interpretation can be seen in the appendix.

Table 5: Simulation results for the current state of urban drainage system of the city of Ayacucho

IDF storm event	Depth [m]	Flow [l/s]	Velocity [m/s]
1h and 5 years of return	0.12	80	1.83
1h and 50 years of return	0.15	110.454	1.97
4h and 5 years of return	0.16	36.16	1.5
4h and 50 years of return	0.2	49.65	1.64
24h and 5 years of return	0.26	11	1.01
24h and 50 years of return	0.33	15.34	1.14

10.2 Application of recommendations

These results show the city runoff after some small changes have been applied. As seen in Figure 11, 3 parts of the chosen urbanisation have been changed to retain stormwater. Two of them are playgrounds and one is a green area. I tried to simulate how would these areas change the runoff if they behaved like a storage unit – that means if the whole area was levelled and lowered by 30cm. This would not affect the current usage of the areas and as seen below, can improve the stormwater management in its surroundings.

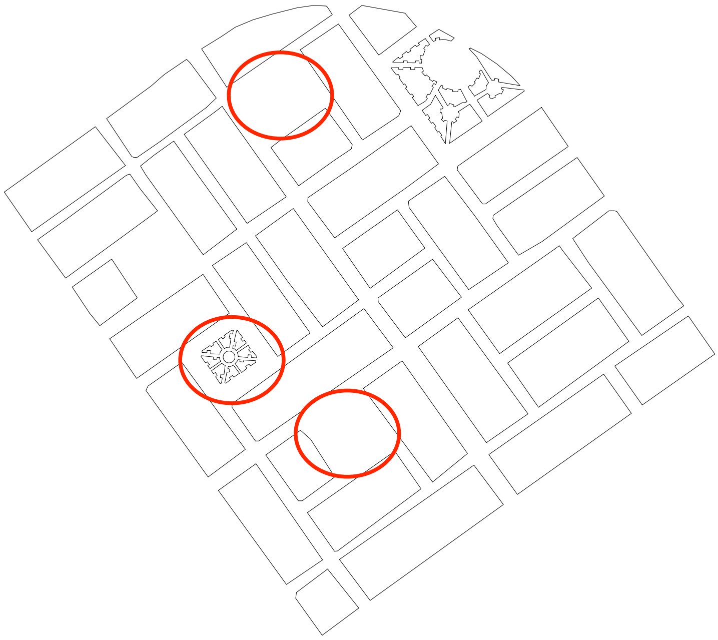

Figure 11: Modified areas

Table 6: Simulation results for the modified state of urban drainage system of the city of Ayacucho

IDF storm event	Depth [m]	Flow [l/s]	Velocity [m/s]
1h and 5 years of return	0.12	68.62	1.66
1h and 50 years of return	0.15	93.84	1.81
4h and 5 years of return	0.16	29.66	1.31
4h and 50 years of return	0.2	40.54	1.62
24h and 5 years of return	0.25	9.16	0.94
24h and 50 years of return	0.33	12.68	1.07

Table 7: Percentual comparison of differences between variables – previous state/modified state of the urban stormwater drainage system

IDF storm event	Depth [%]	Flow [%]	Velocity [%]
1h and 5 years of return	0	16.6	10.2
1h and 50 years of return	0	17.7	8.8
4h and 5 years of return	0	21.9	14.5
4h and 50 years of return	0	22.5	1.2
24h and 5 years of return	4	20.1	7.4
24h and 50 years of return	0	21	6.5

As can be seen in Table 6 the biggest improvement is in flow, where during a precipitation event of 4h with a 50 years return period we can observe a 22.5% difference in maximal flow. Even though depth is most likely unaffected by these changes, the decrease of velocity by 14.5% in the event of 4h duration precipitation with a 5 years of return period is a noticeable difference.

11 Conclusions

The thesis started with description and comparison of legislation and climatic differences of the Czech Republic and Peru in Chapter 4. As described, the conditions are dissimilar and the whole approach to both countries in terms of stormwater management must be sensitive and distinct.

Next the city of Ayacucho and its urban drainage stormwater system was described in Chapter 6. This part of the thesis proved unfortunate because of availability of data, translation work and general difficulties in text comprehension for a person not familiar with conditions and problems of Peru. Since the progression of sustainable development, both countries are trying to apply its principles into the infrastructure and designs of stormwater management. As such, more developed countries should be leading this new way of approach in such a way, that developing countries should be able to implement these measures without difficulties and errors.

Thanks to data from Peru I was able to create and use a simulation in the SWMM software in which I analysed the current stormwater drainage system, evaluated the results, applied recommendations and compared those results in Chapters 7 to 10. The quality of the simulation is heavily dependent on data and there will always be room for improvement.

From the results in Chapter 10 can be observed, that the current system of drainage the city of Ayacucho, in the small simulated part of the city at least, is currently working but can be modified to meet the requirements of the modern approach to be more sensitive to the environment, to achieve higher level of citizens safety and to increase the living comfort in the city (at least aesthetically).

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13 Appendix

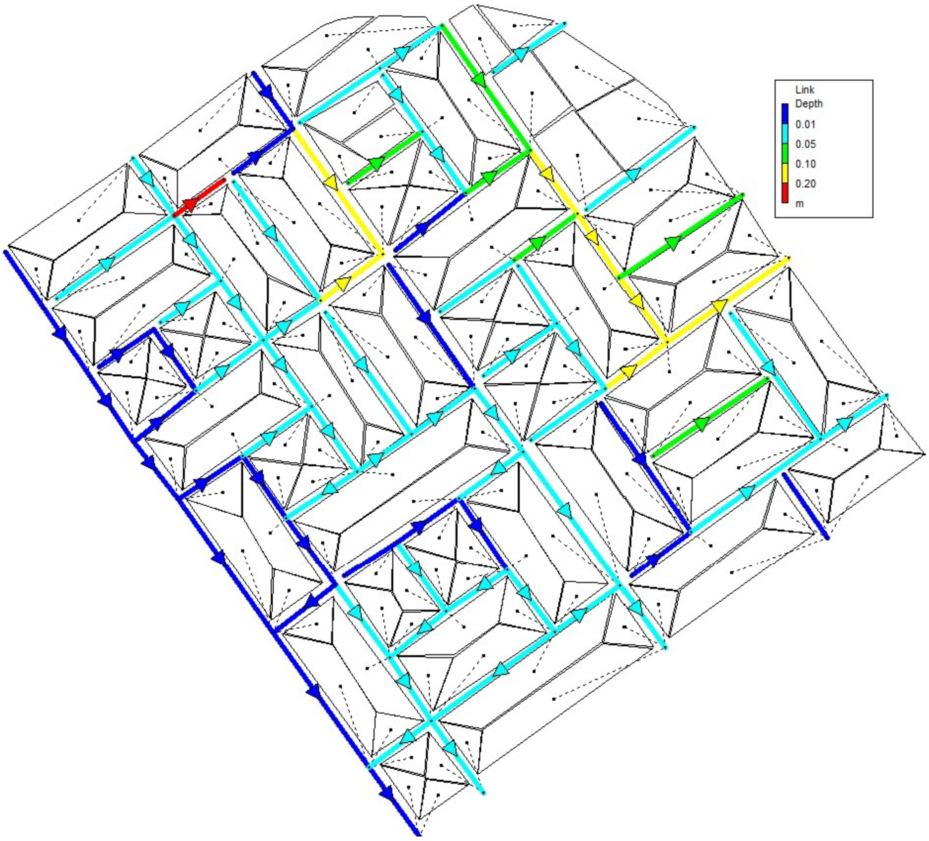

Figure 12: IDF storm event of 1h and 5 years of return – depth.

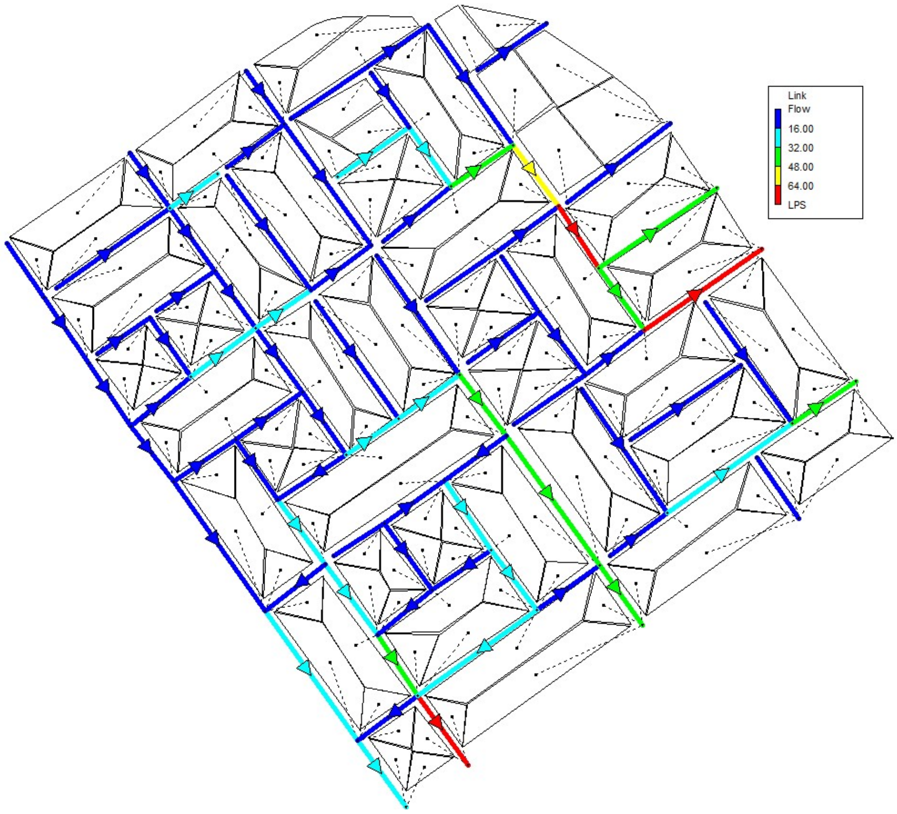

Figure 13: IDF storm event of 1h and 5 years of return – flow.

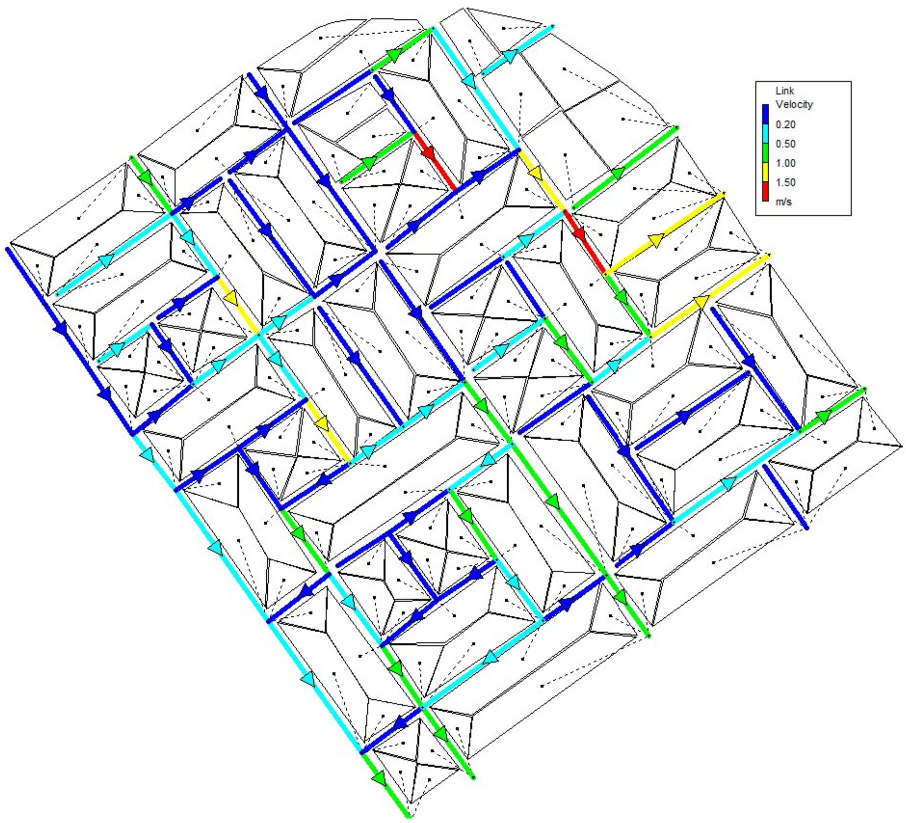

Figure 14: IDF storm event of 1h and 5 years of return – velocity.

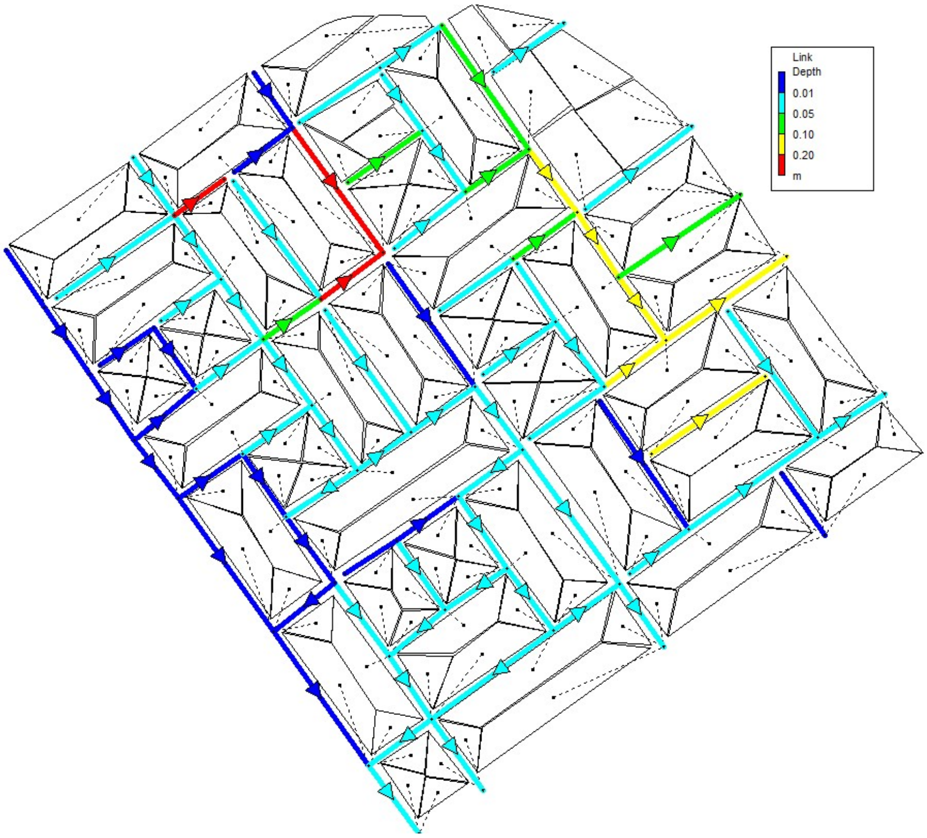

Figure 15: IDF storm event of 1h and 50 years of return – depth.

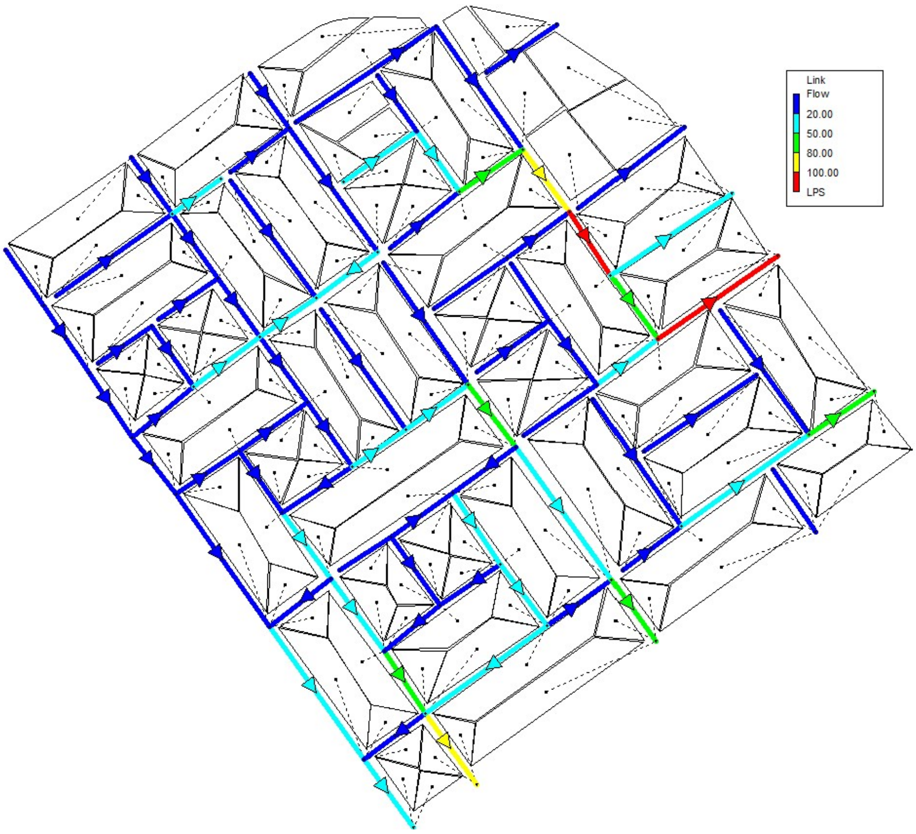

Figure 16: IDF storm event of 1h and 50 years of return – flow.

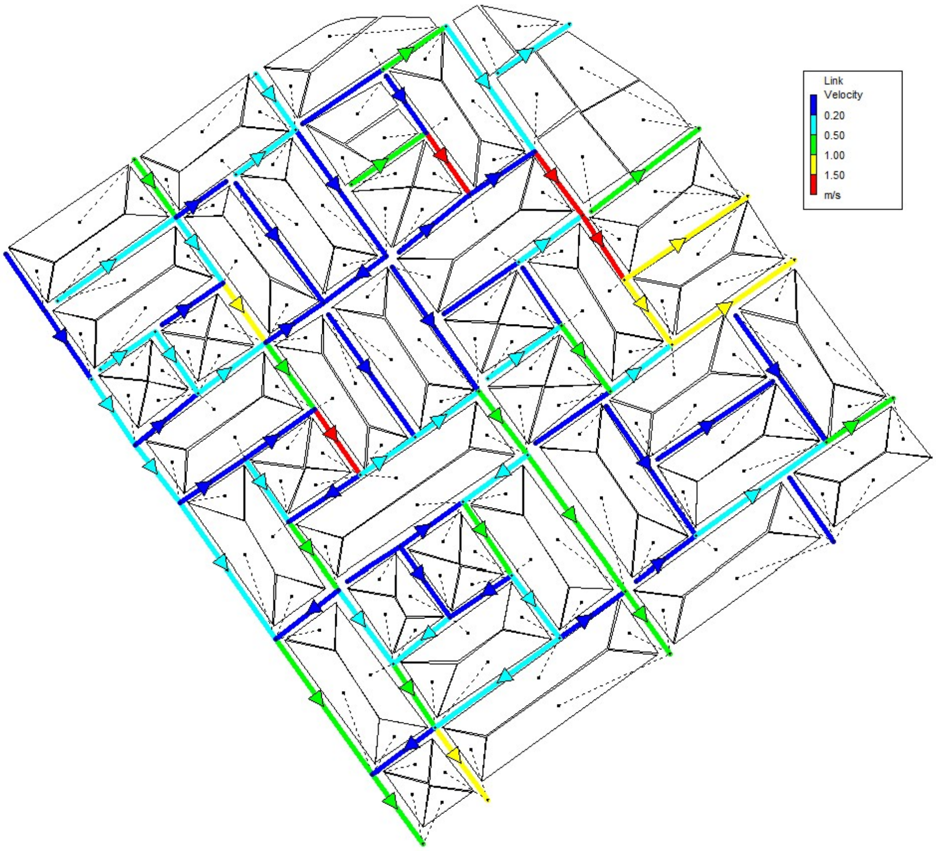

Figure 17: IDF storm event of 1h and 50 years of return – velocity.

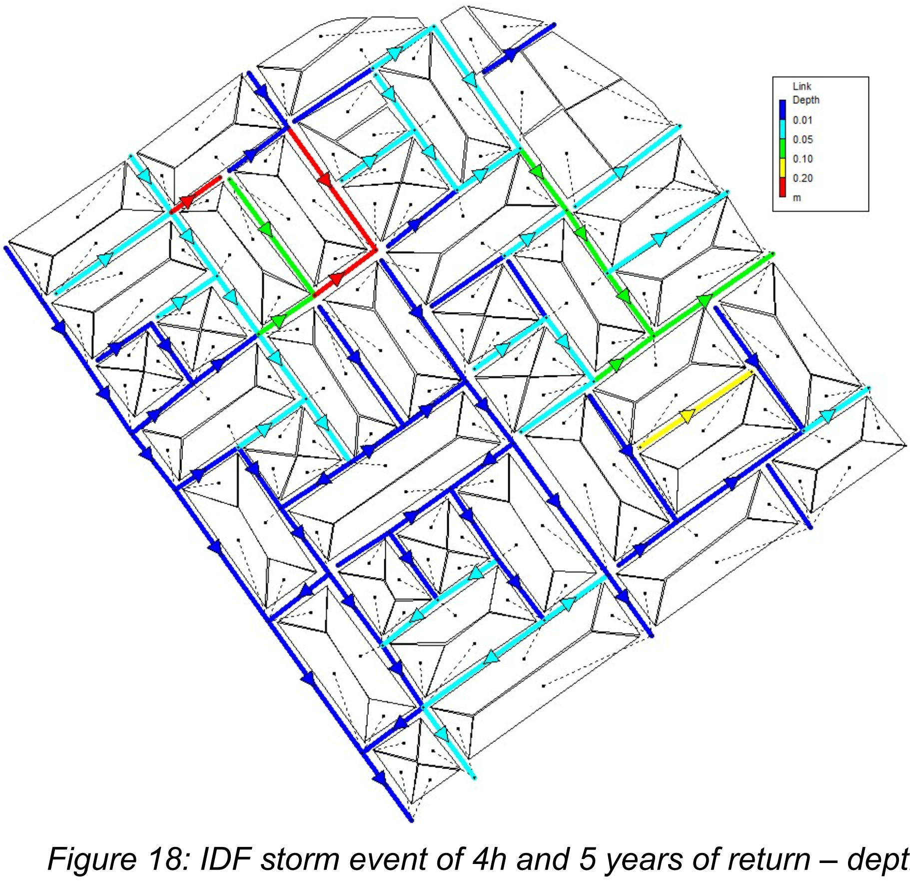

Figure 18: IDF storm event of 4h and 5 years of return – depth.

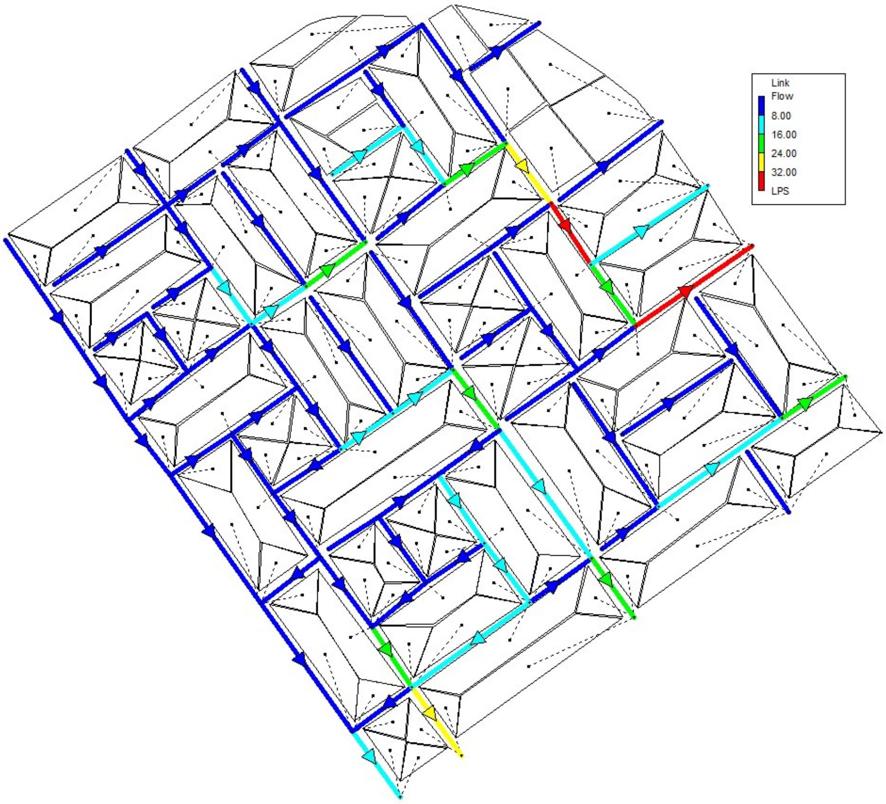

Figure 19: IDF storm event of 4h and 5 years of return – flow.

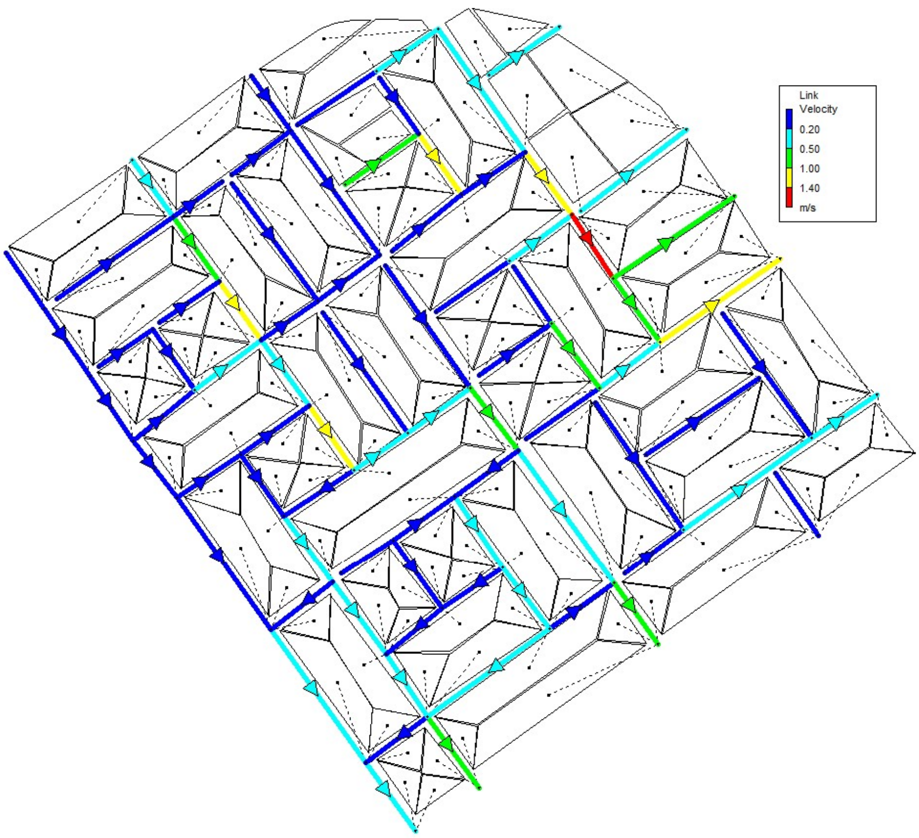

Figure 20: IDF storm event of 4h and 5 years of return – velocity.

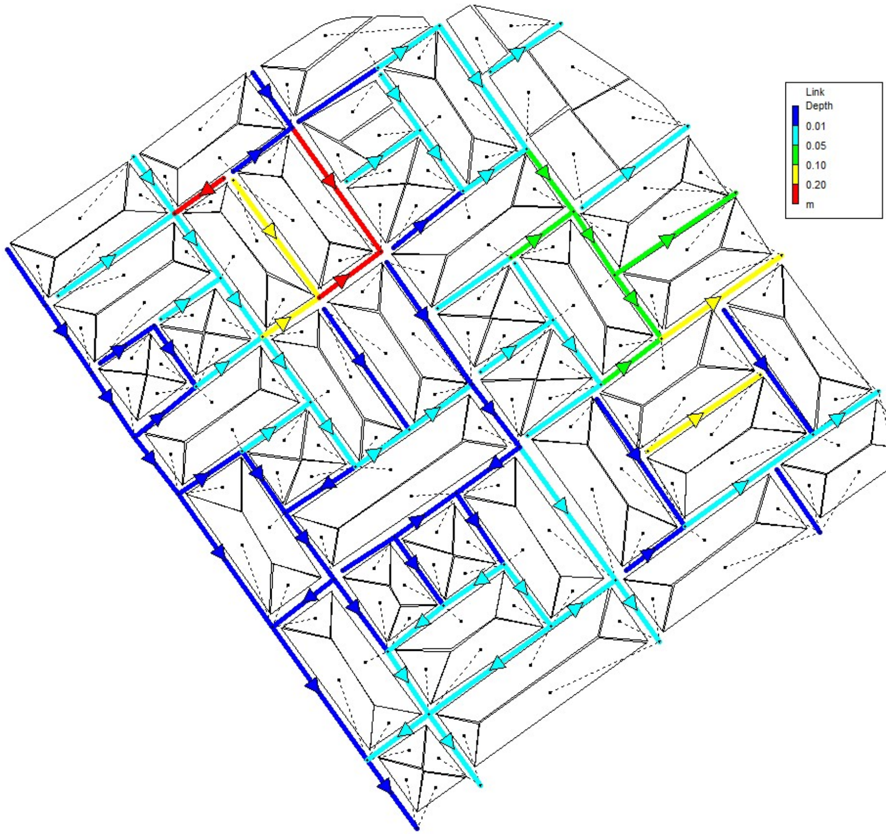

Figure 21: IDF storm event of 4h and 50 years of return – depth.

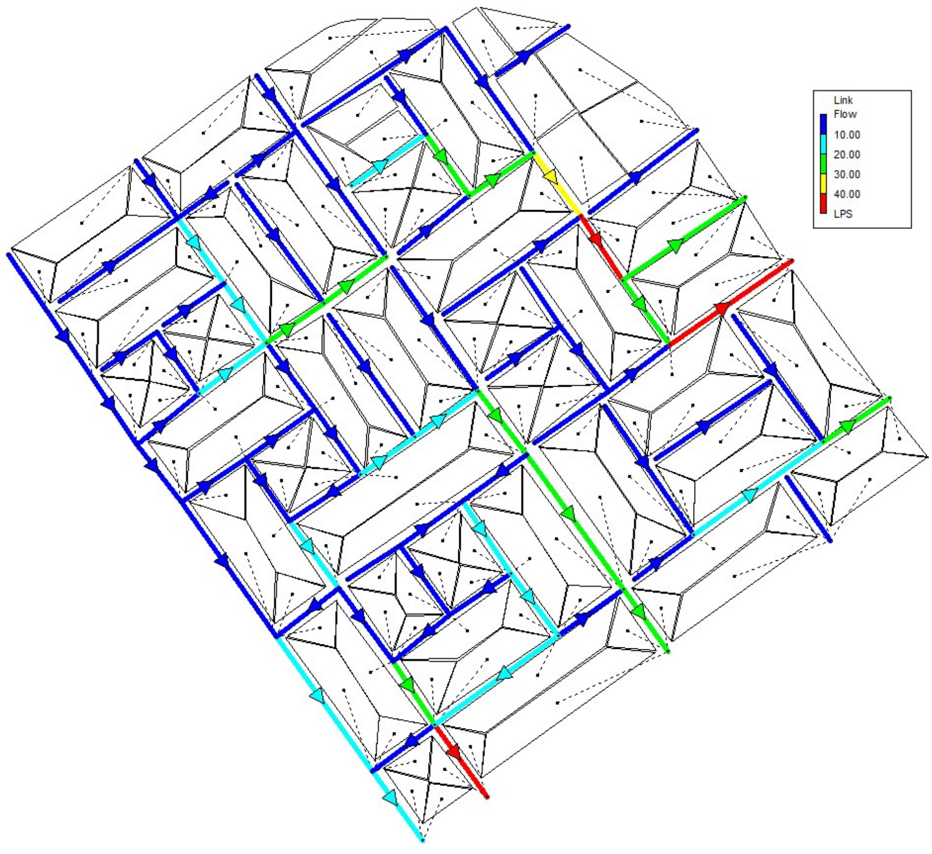

Figure 22: IDF storm event of 4h and 50 years of return – flow.

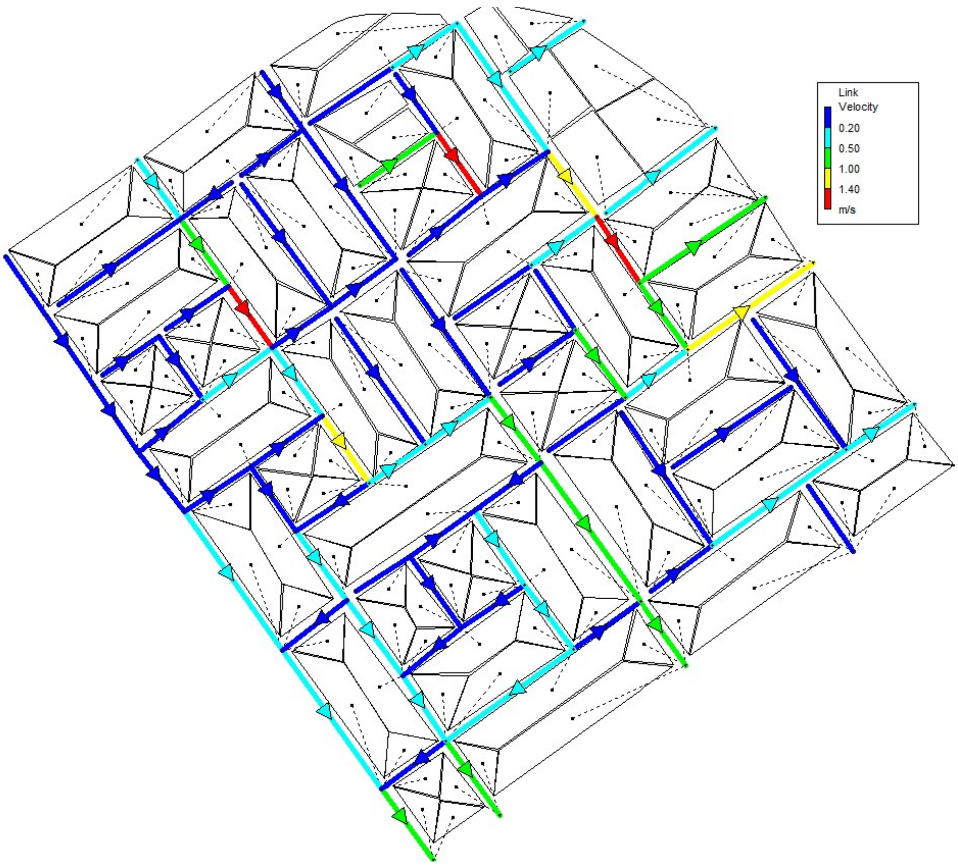

Figure 23: IDF storm event of 4h and 50 years of return – velocity.

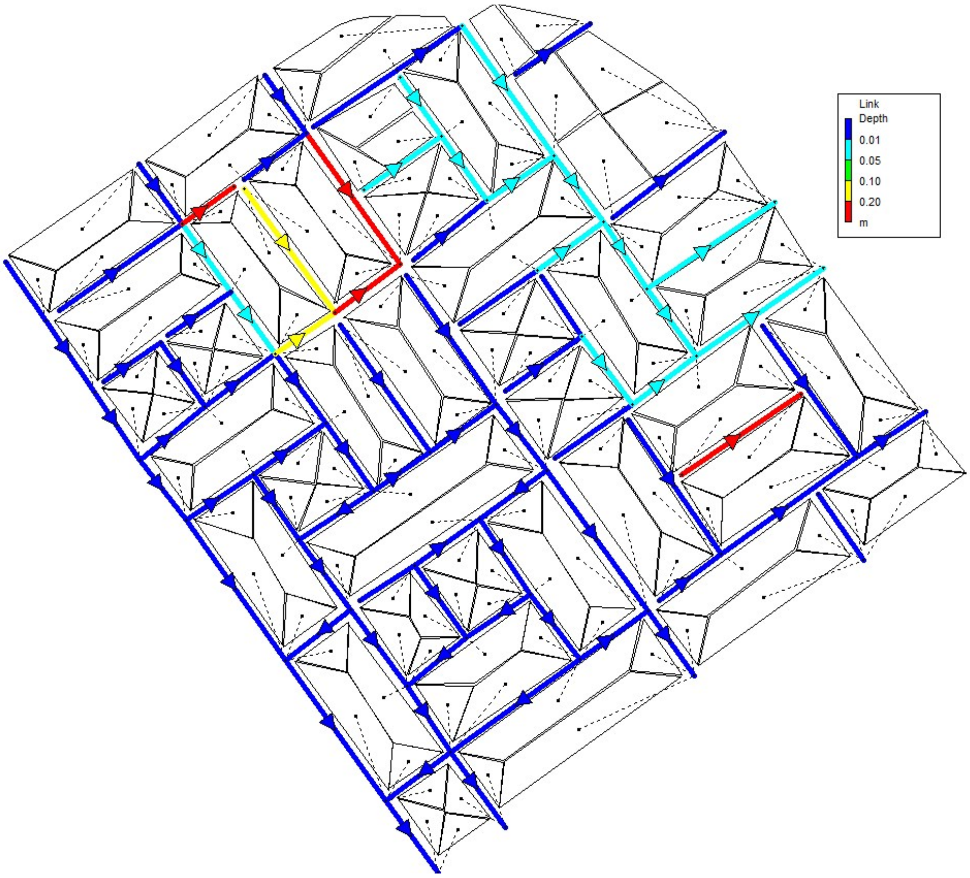

Figure 24: IDF storm event of 24h and 5 years of return – depth.

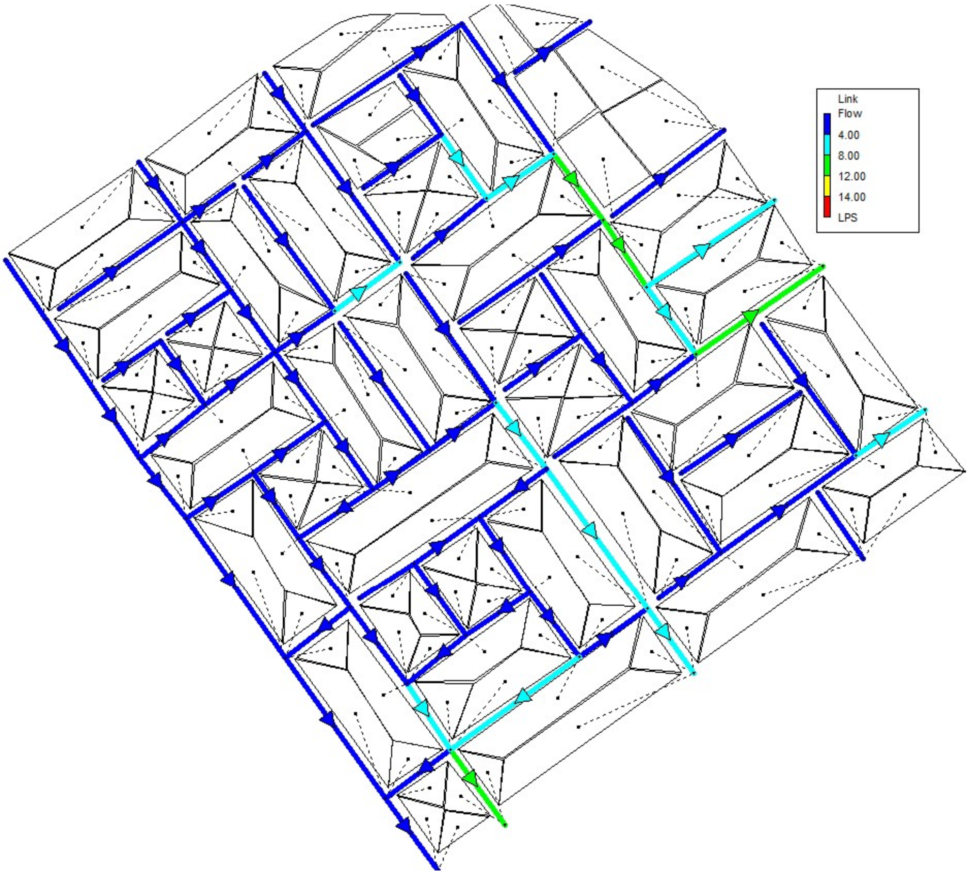

Figure 25: IDF storm event of 24h and 5 years of return – flow.

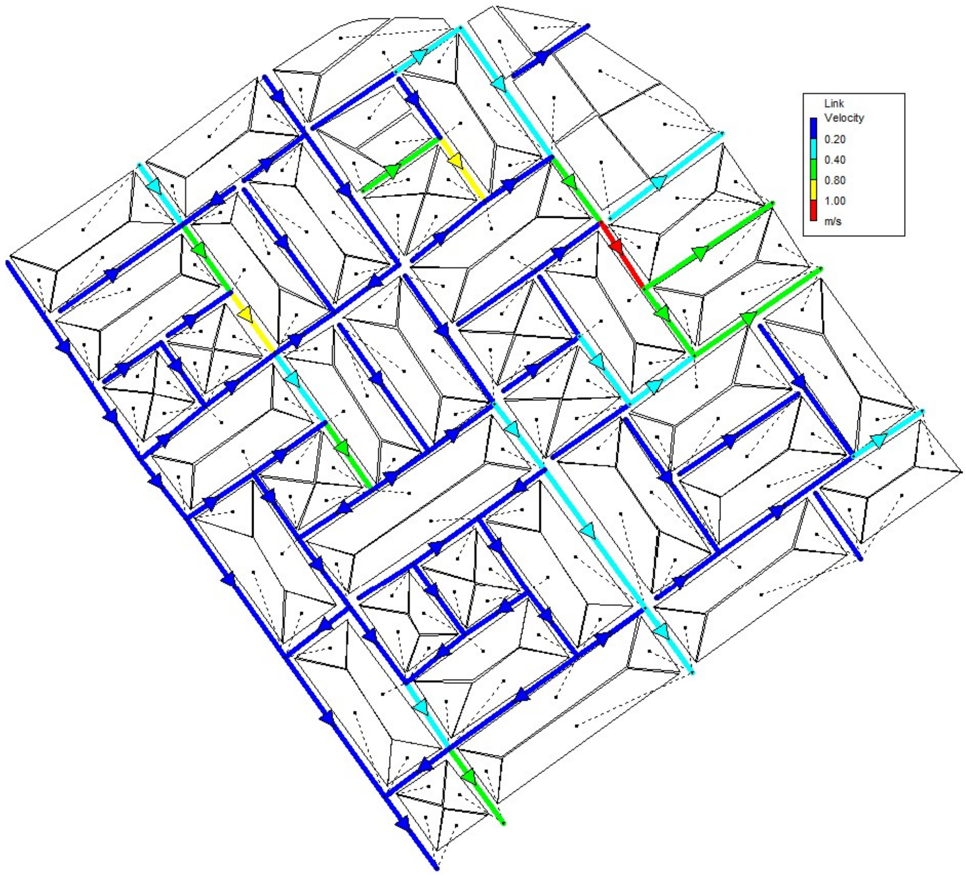

Figure 26: IDF storm event of 24h and 5 years of return – velocity.

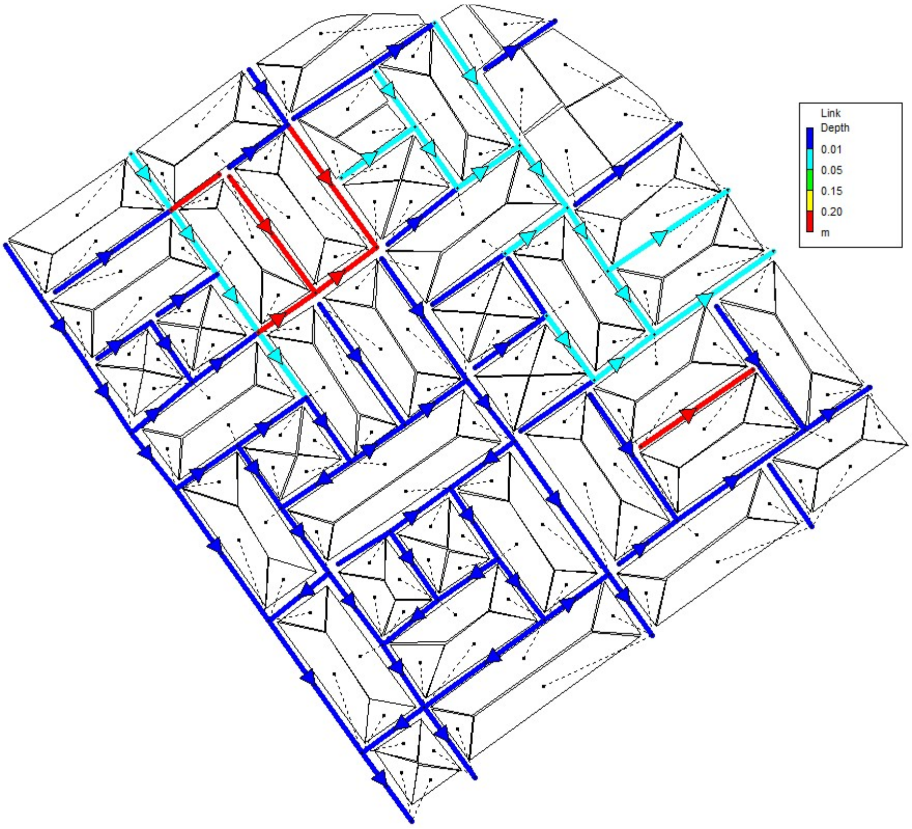

Figure 27: IDF storm event of 24h and 50 years of return – depth.

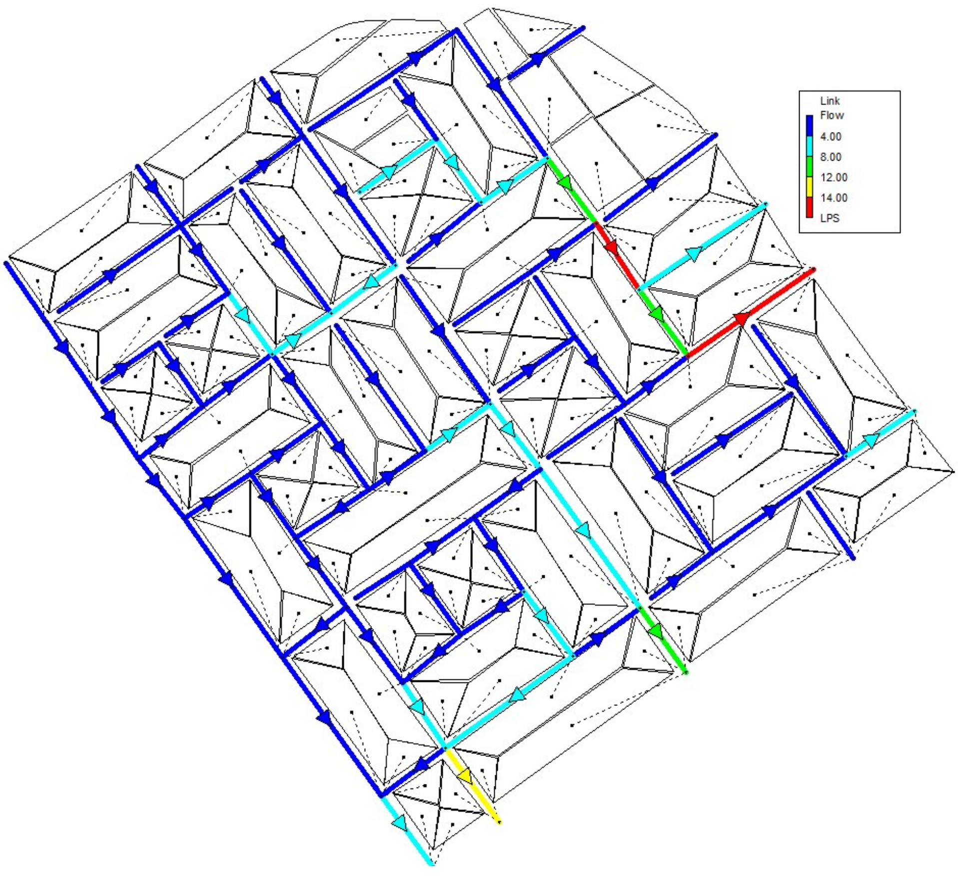

Figure 28: IDF storm event of 24h and 50 years of return – flow.

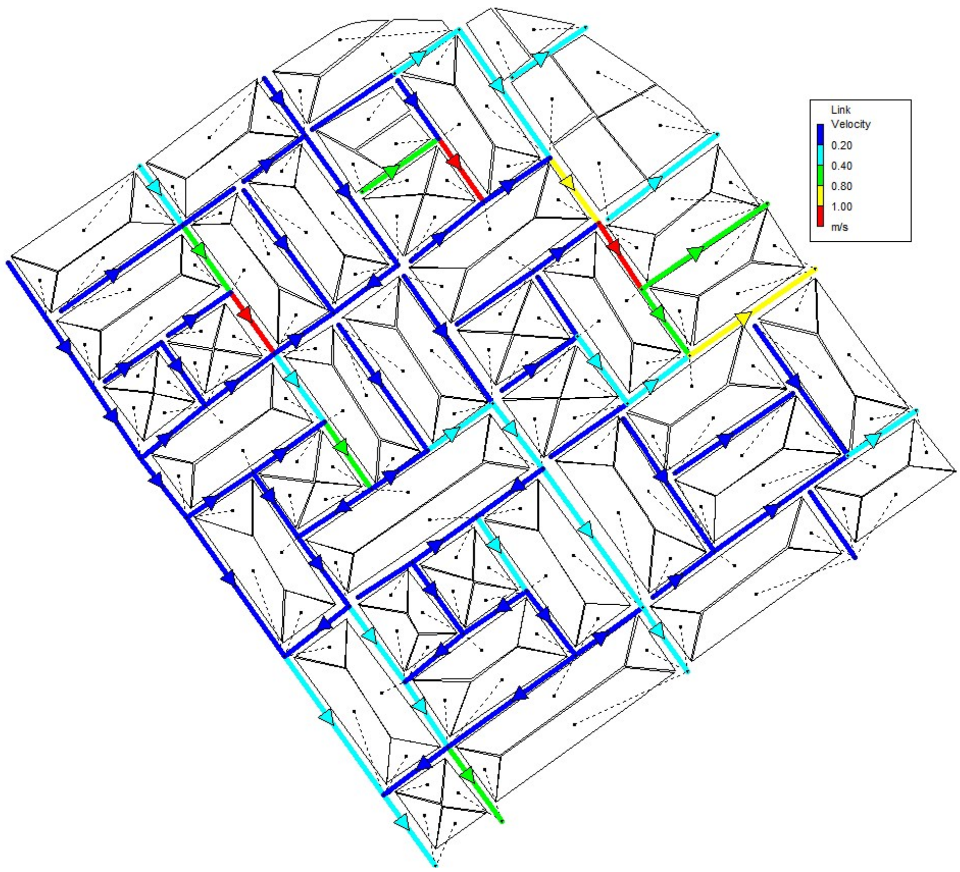

Figure 29: IDF storm event of 24h and 50 years of return – velocity.

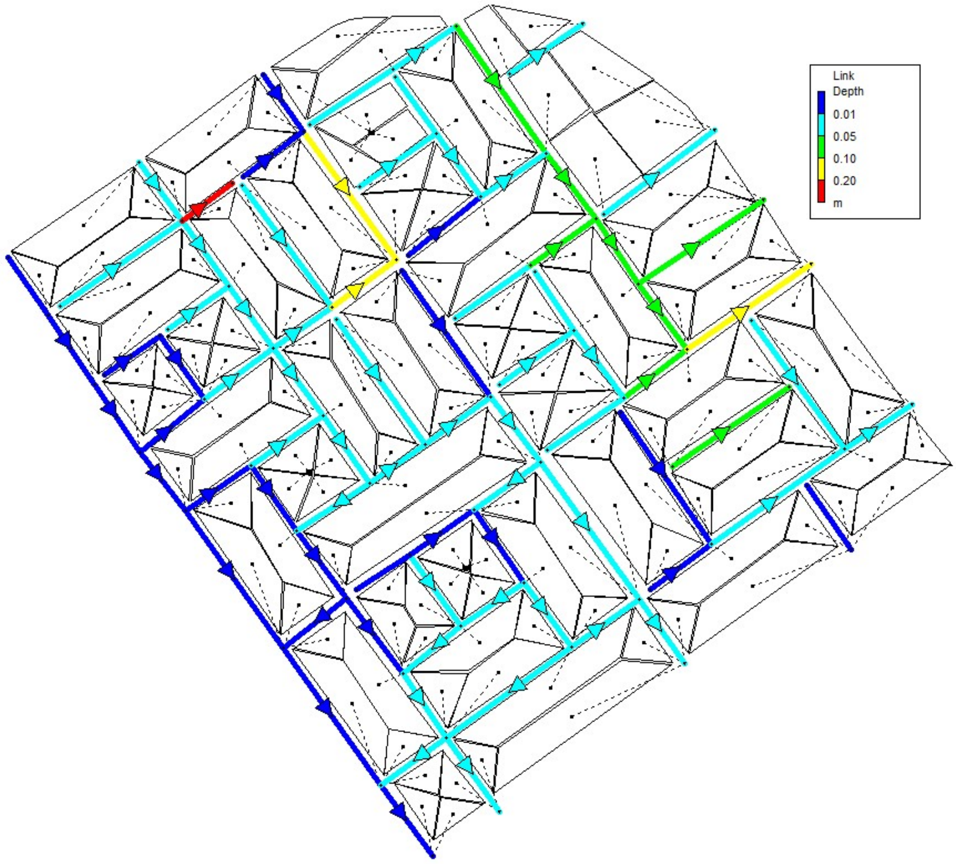

Figure 30: Modified area - IDF storm event of 1h and 5 years of return – depth.

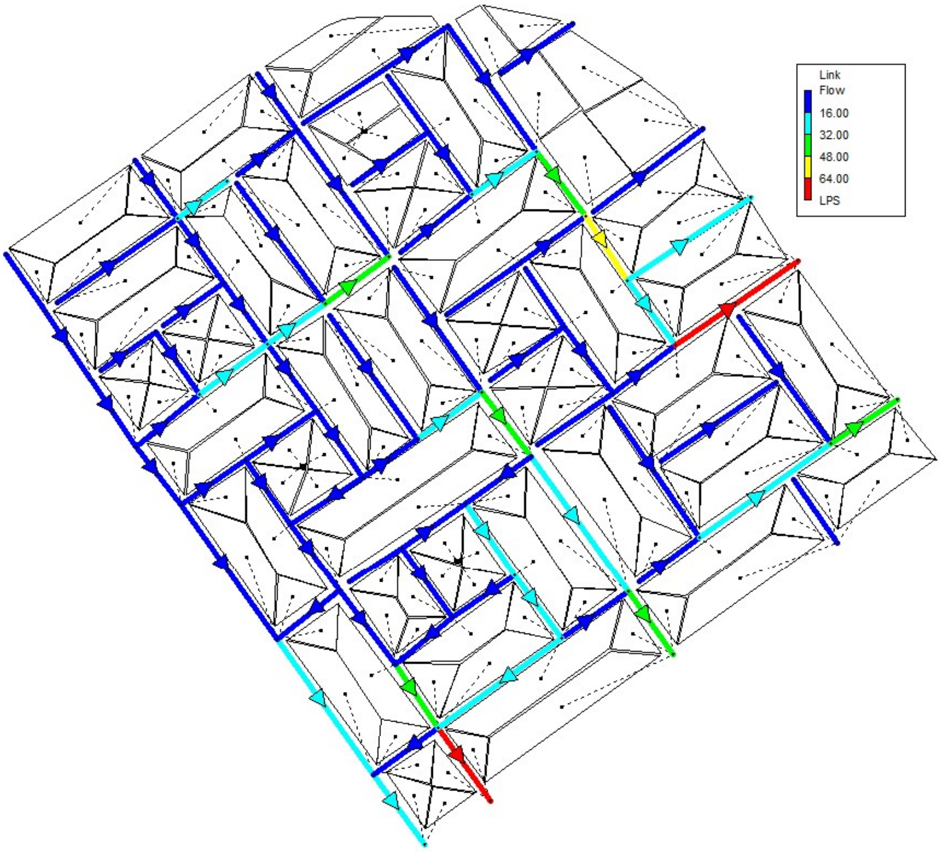

Figure 31: Modified area - IDF storm event of 1h and 5 years of return – flow.

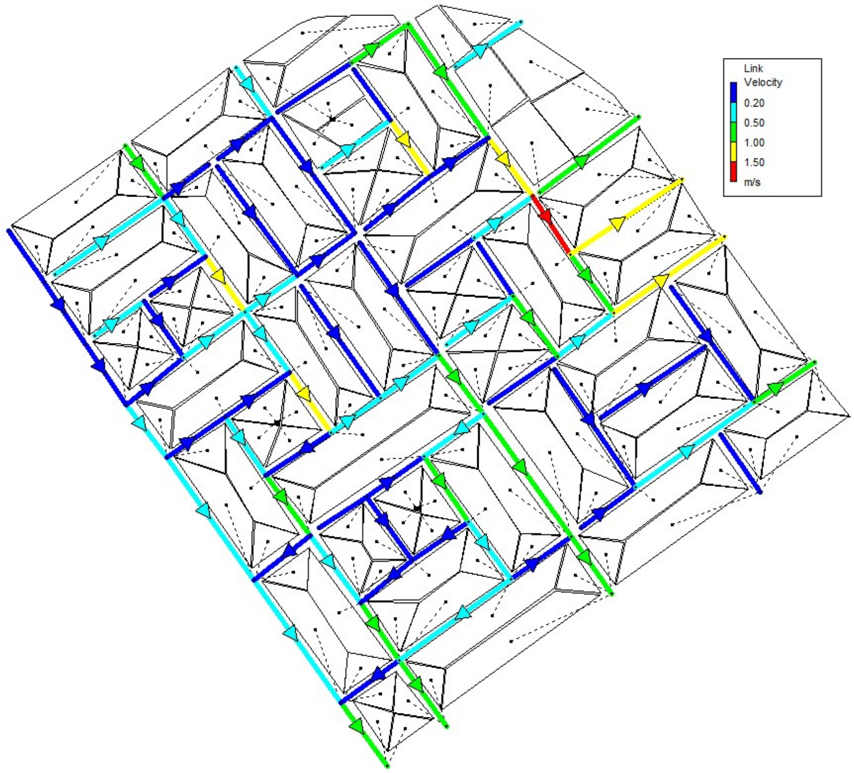

Figure 32: Modified area - IDF storm event of 1h and 5 years of return – velocity.

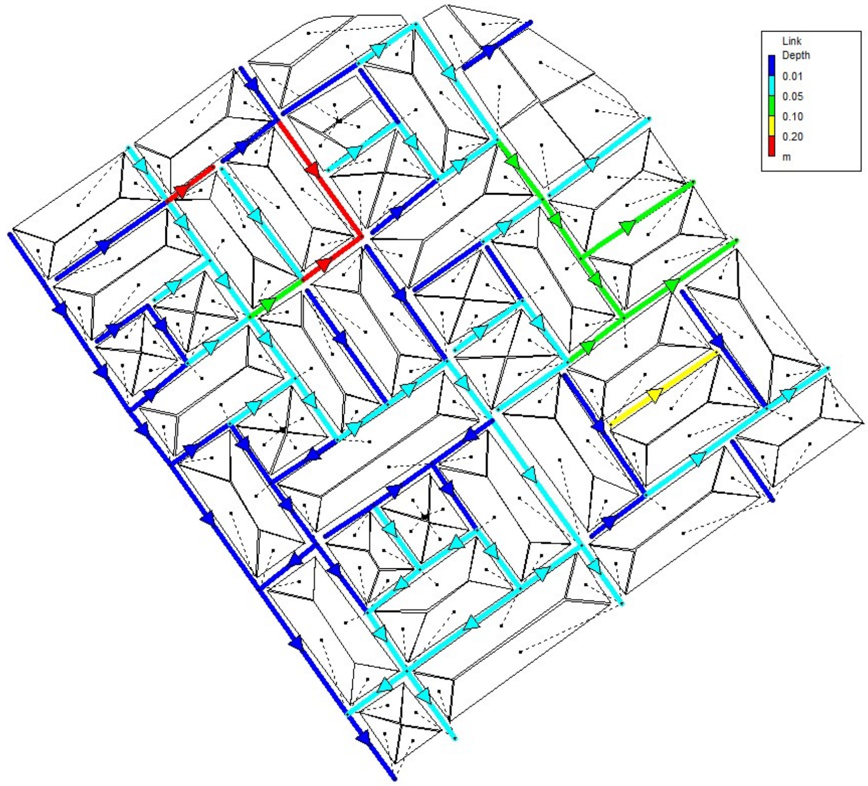

Figure 33: Modified area - IDF storm event of 1h and 50 years of return – depth.

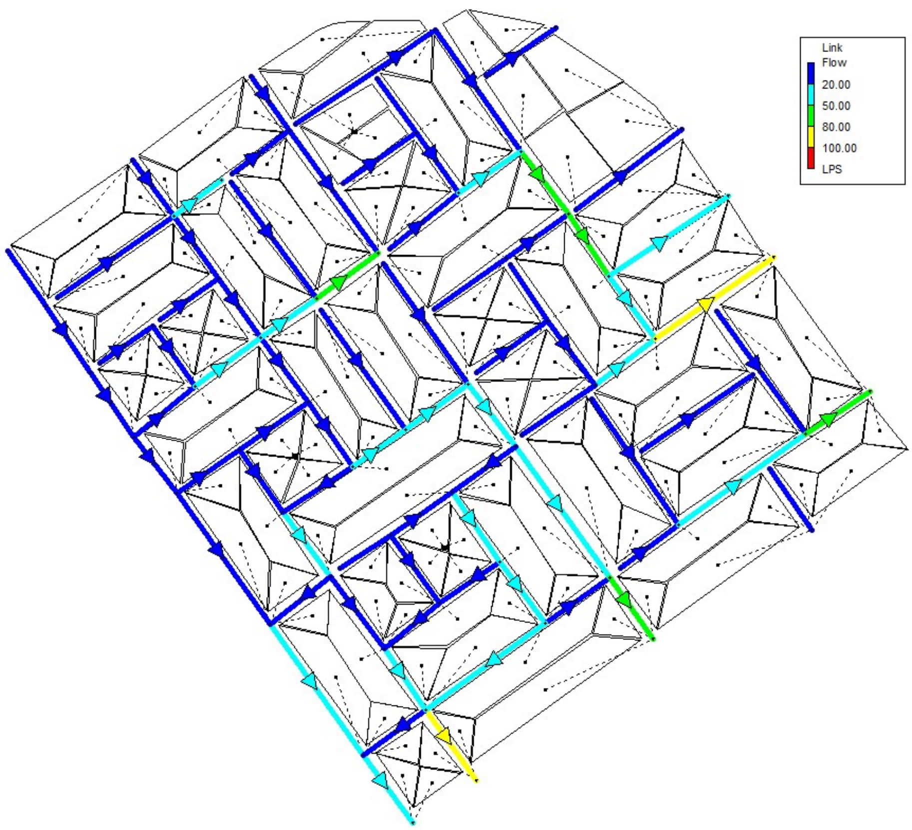

Figure 34: Modified area - IDF storm event of 1h and 50 years of return – flow.

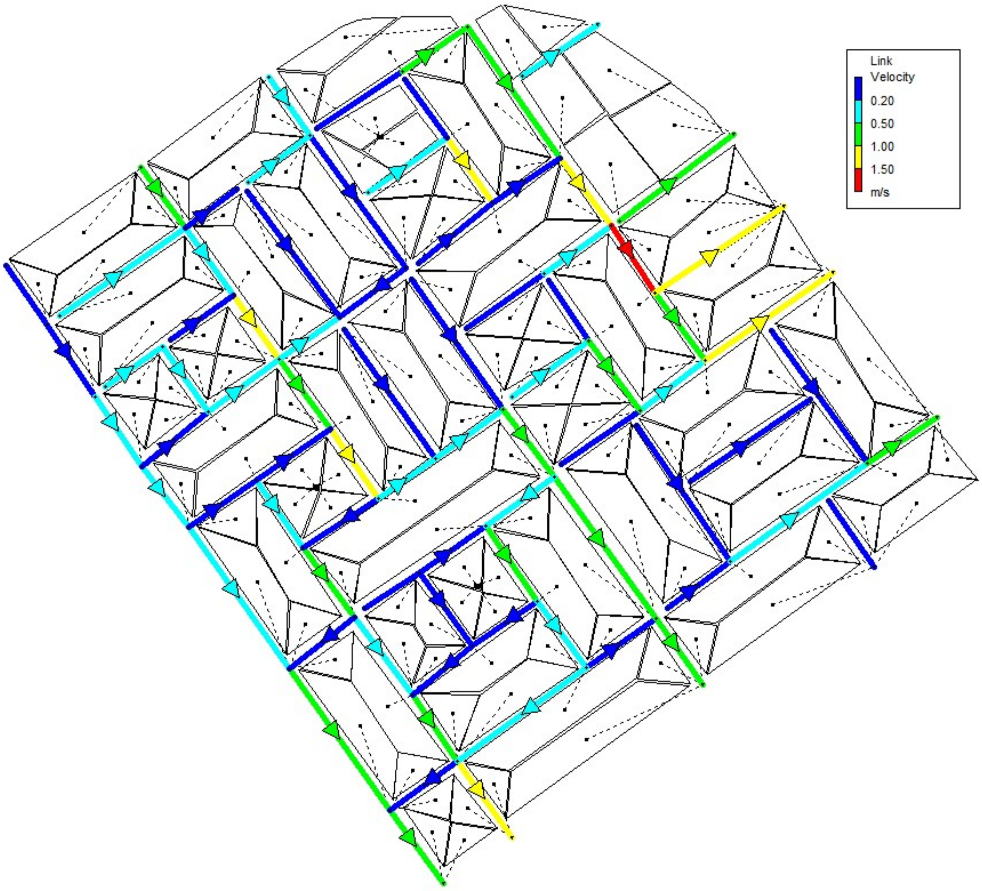

Figure 35: Modified area - IDF storm event of 1h and 50 years of return – velocity.

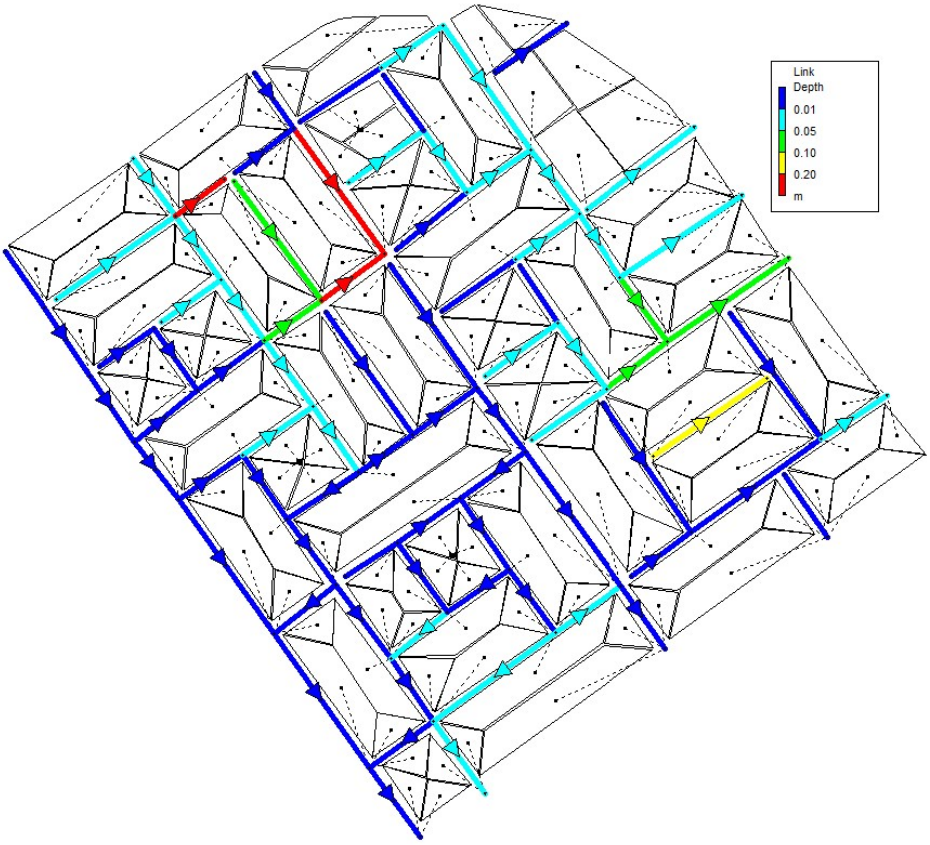

Figure 36: Modified area - IDF storm event of 4h and 5 years of return – depth.

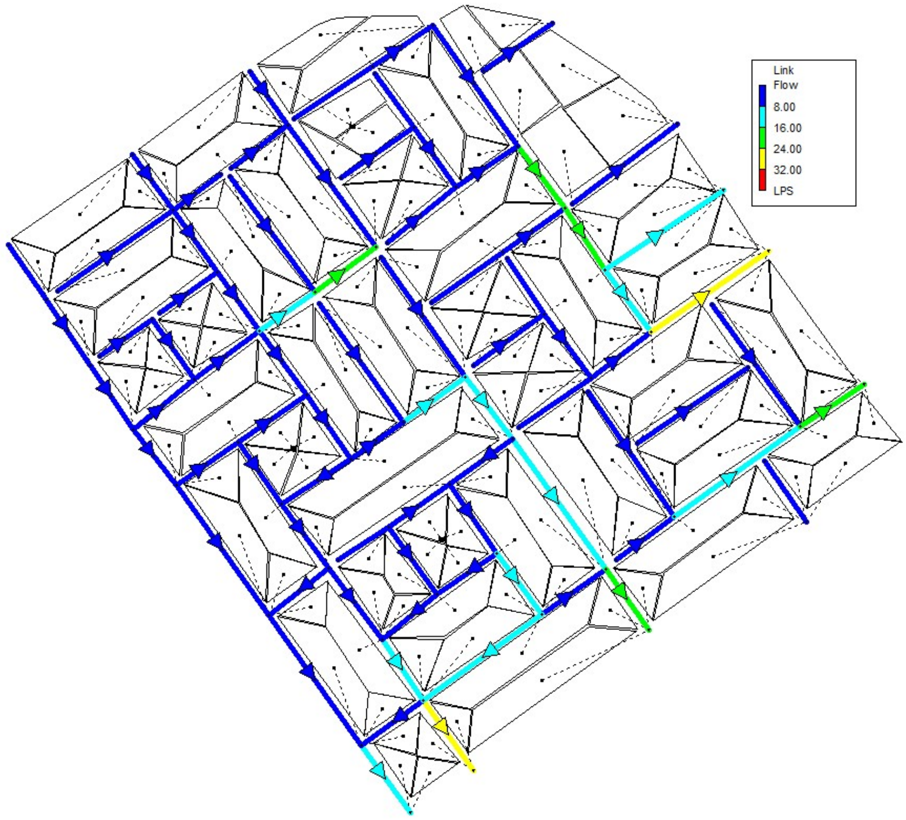

Figure 37: Modified area - IDF storm event of 4h and 5 years of return – flow.

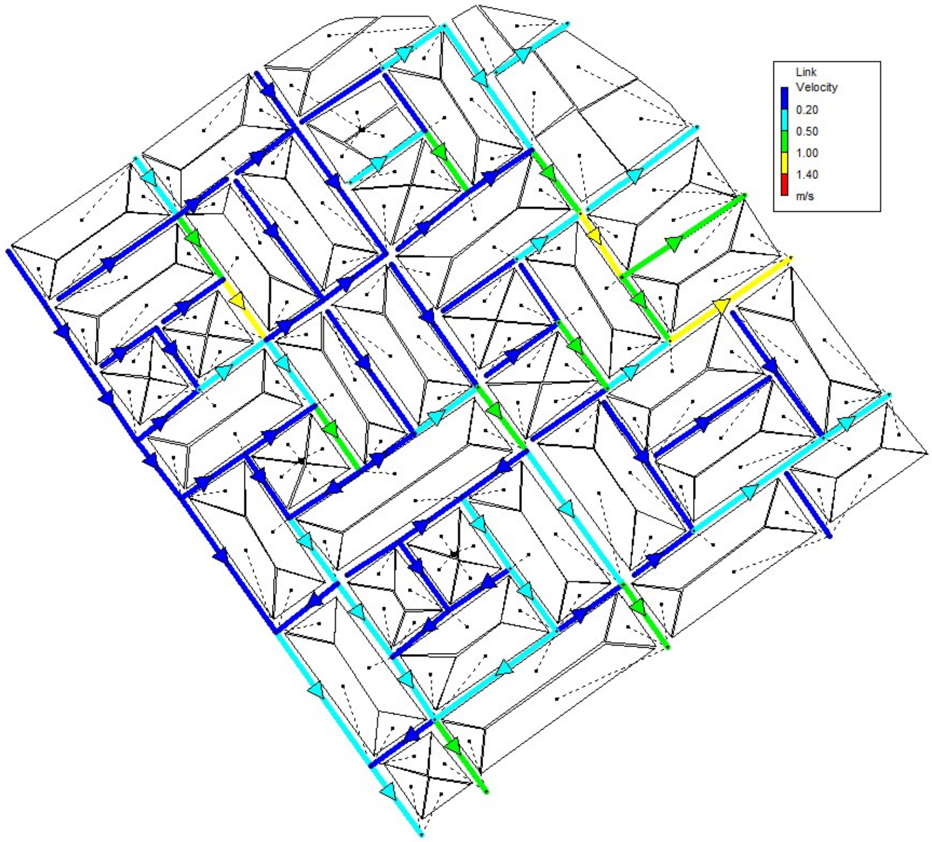

Figure 38: Modified area - IDF storm event of 4h and 5 years of return – velocity.

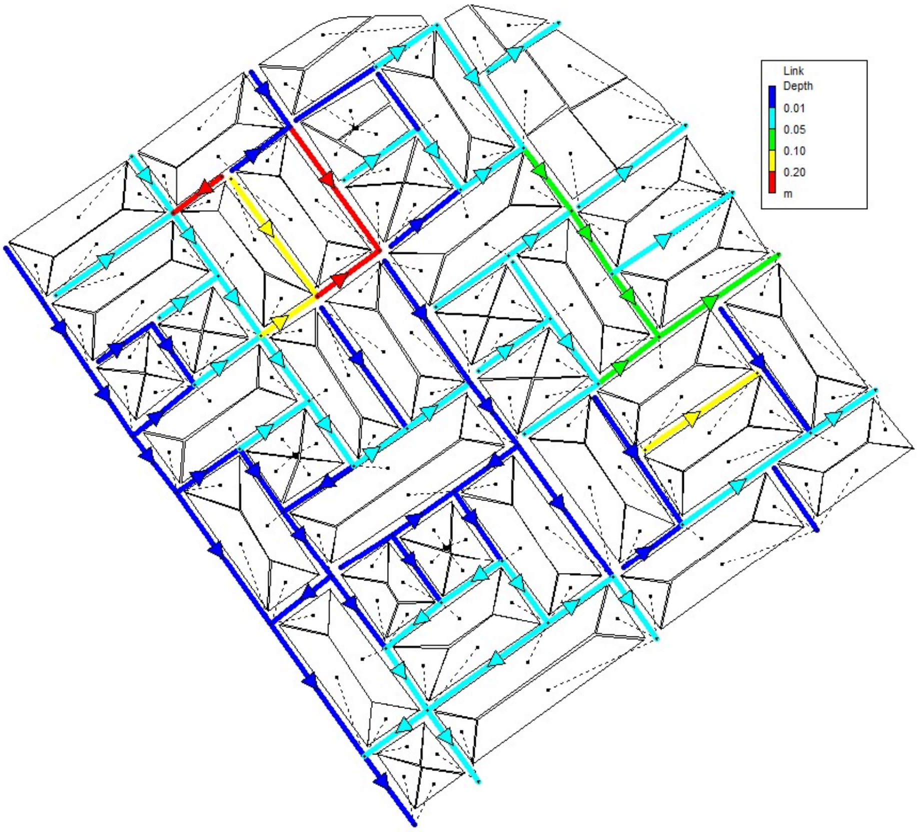

Figure 39: Modified area - IDF storm event of 4h and 50 years of return – depth.

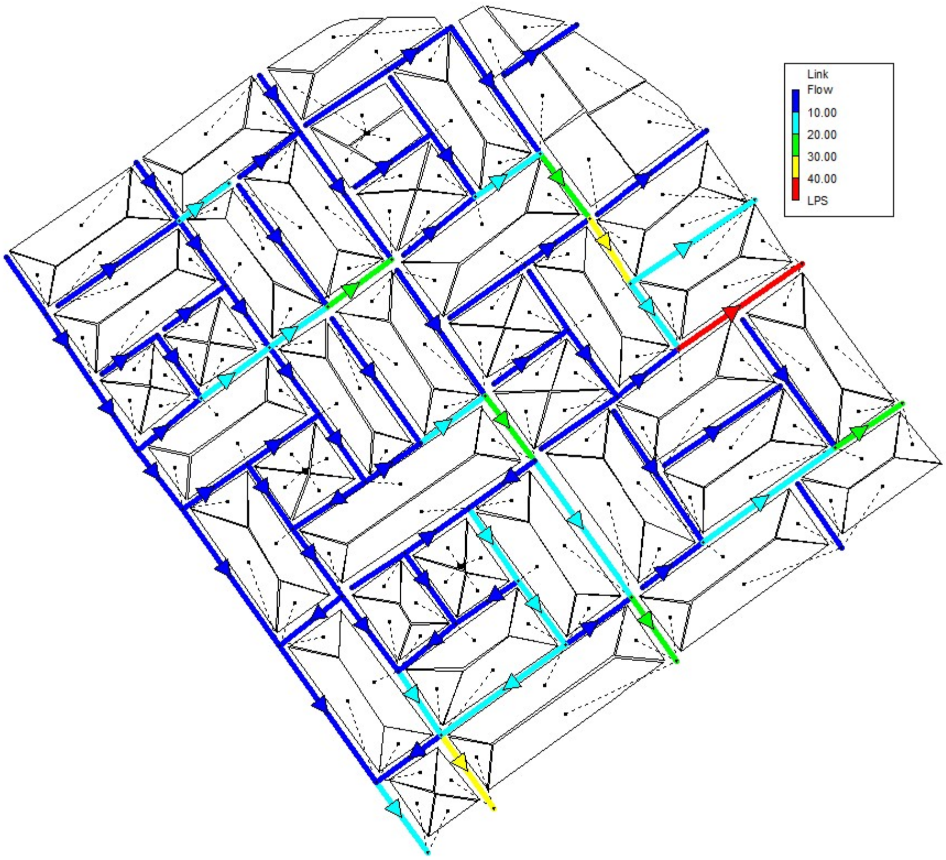

Figure 40: Modified area - IDF storm event of 4h and 50 years of return – flow.

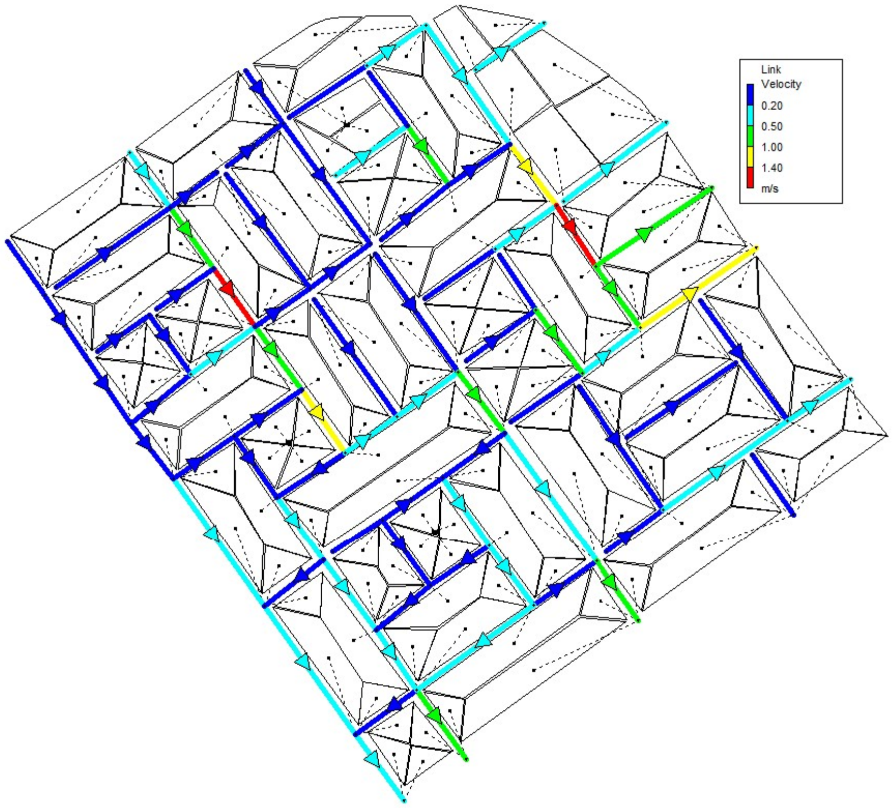

Figure 41: Modified area - IDF storm event of 4h and 50 years of return – velocity.

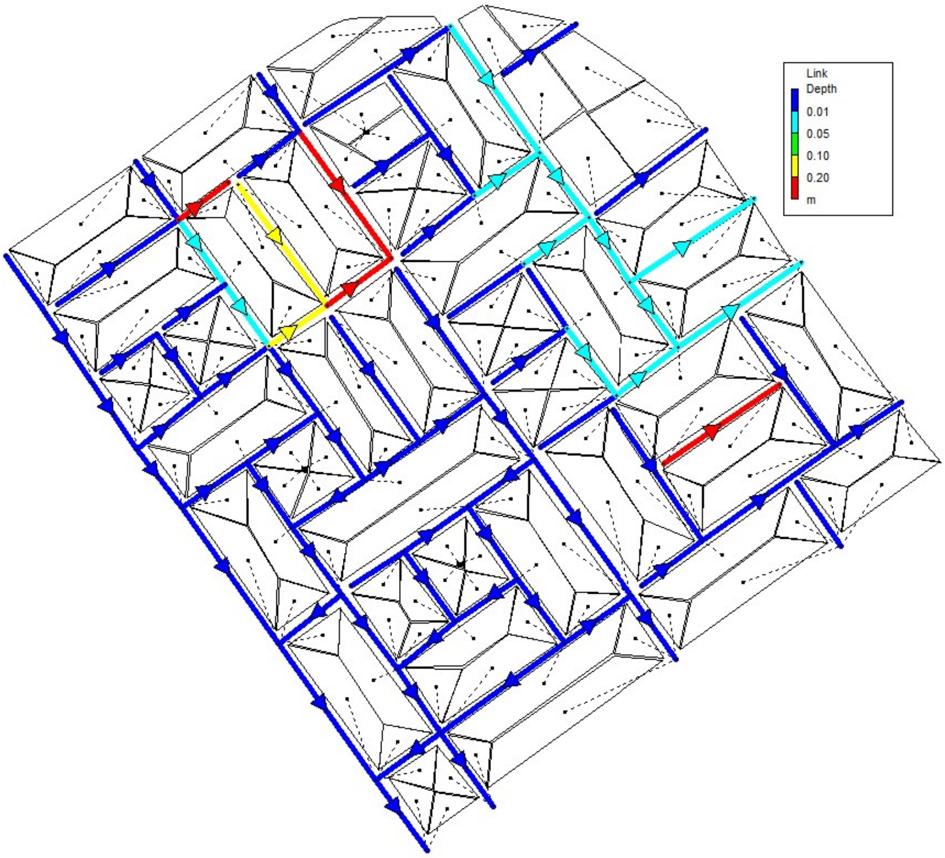

Figure 42: Modified area - IDF storm event of 24h and 5 years of return – depth.

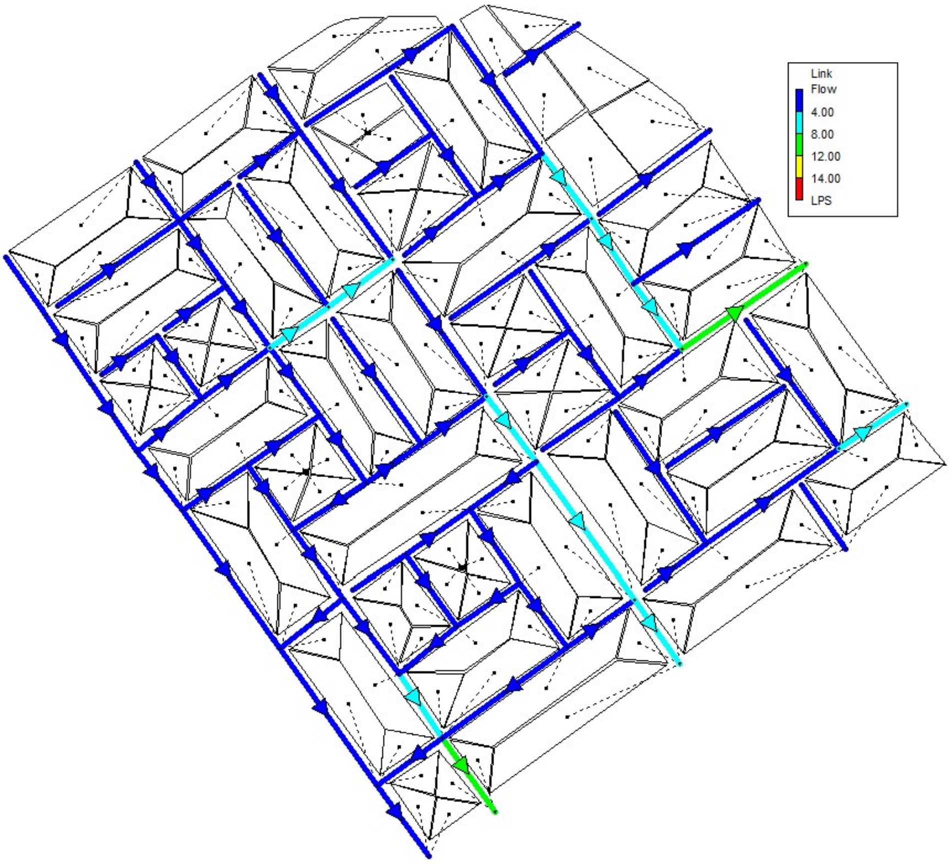

Figure 43: Modified area - IDF storm event of 24h and 5 years of return – flow.

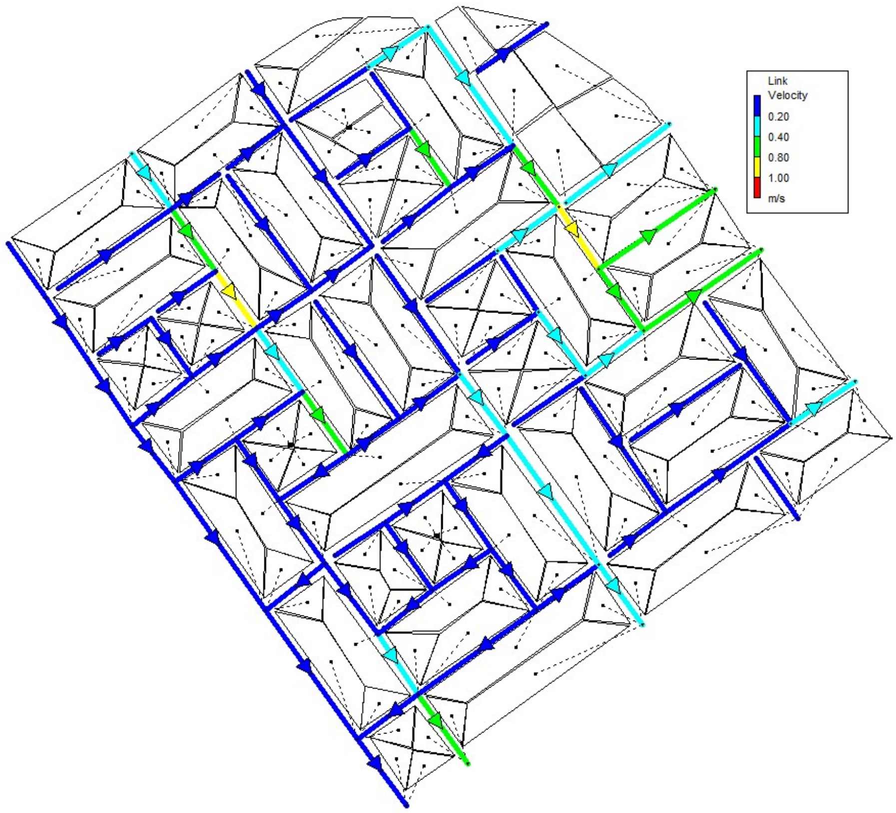

Figure 44: Modified area - IDF storm event of 24h and 5 years of return – velocity.

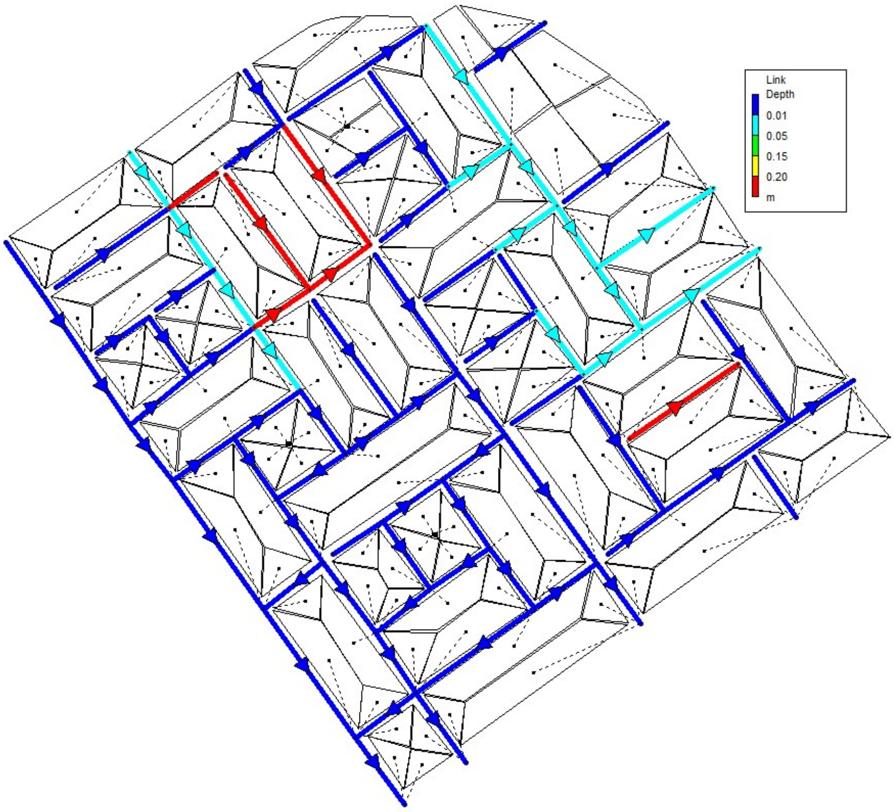

Figure 45: Modified area - IDF storm event of 24h and 50 years of return – depth.

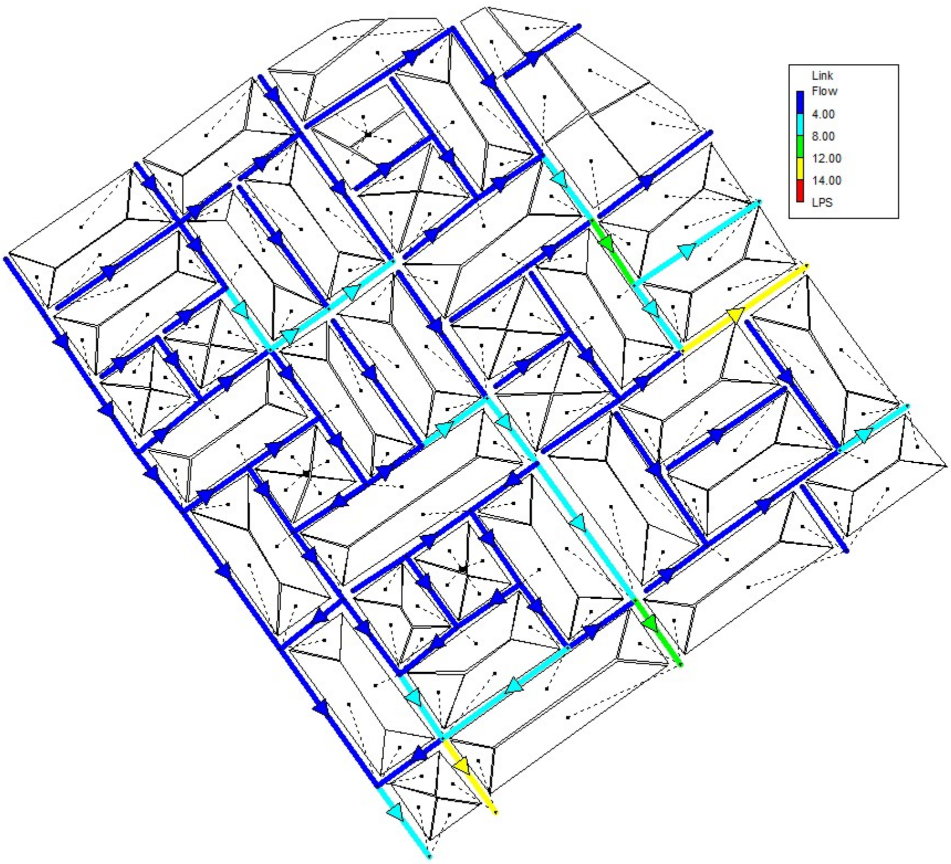

Figure 46: Modified area - IDF storm event of 24h and 50 years of return – flow.

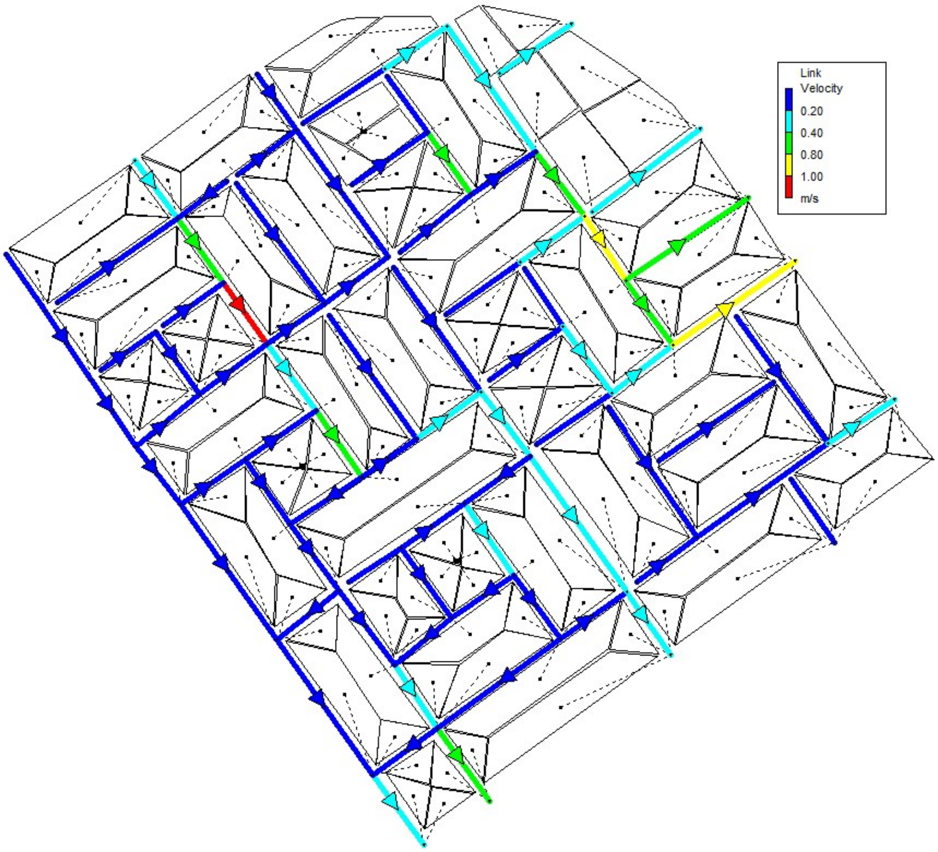

Figure 47: Modified area - IDF storm event of 24h and 50 years of return – velocity.